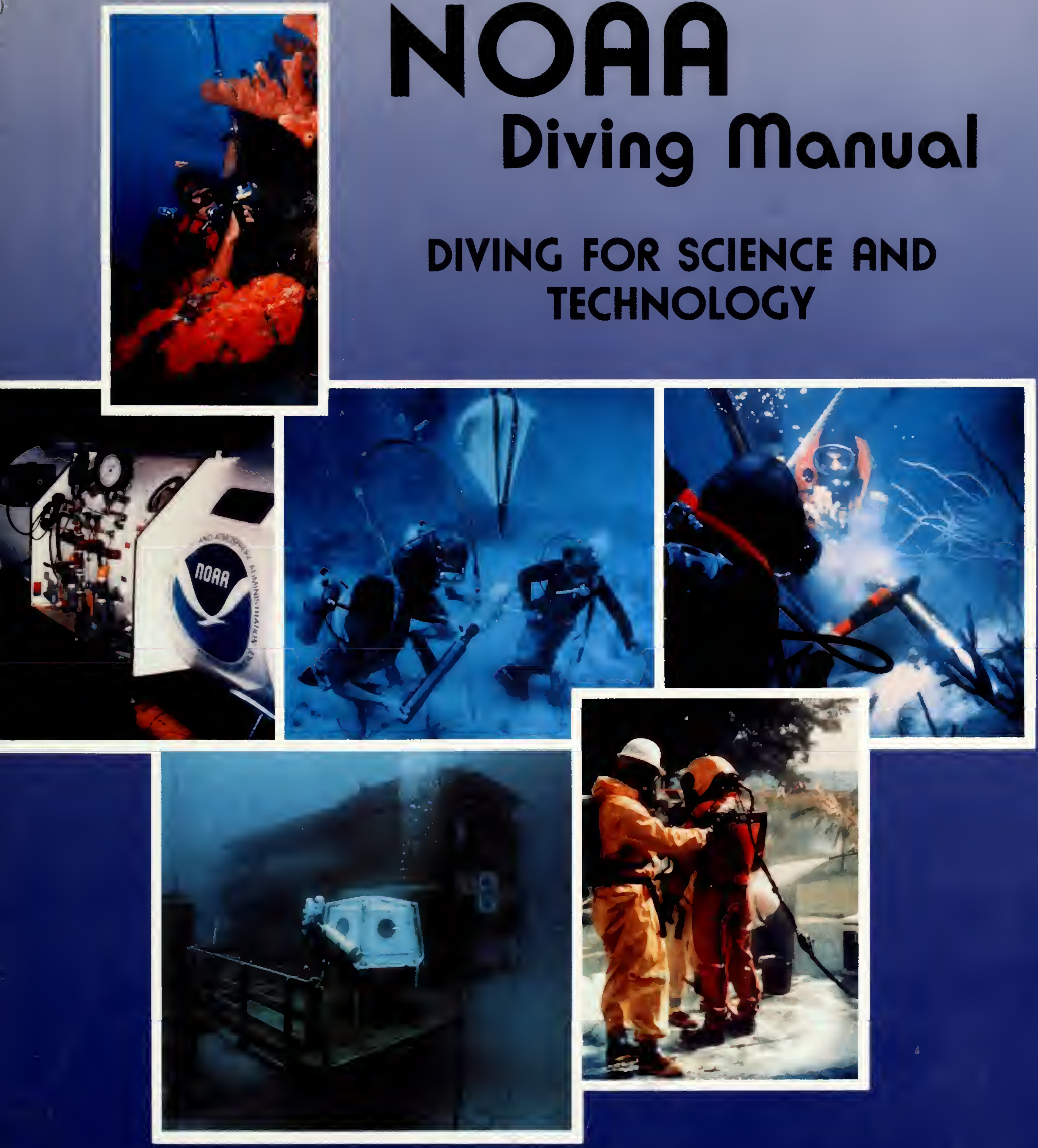
NOAA
Diving Manual

DIVING FOR SCIENCE AND TECHNOLOGY



U.S. DEPARTMENT OF COMMERCE

NOAA DIVING MANUAL

DIVING FOR SCIENCE AND TECHNOLOGY

October 1991

U.S. DEPARTMENT OF COMMERCE
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FOREWORD

NOAA, the largest component of the Department of Commerce, is an agency with a broad mission in environmental monitoring, prediction, and understanding of the oceans and the atmosphere. I call NOAA the "earth systems agency" because it studies the relationship between the natural components of our planet. Among the most important duties we perform is the monitoring of the oceans and Laurentide Great Lakes.

NOAA operates a variety of sensors and platforms that permit observation and measurement of change in the seas and Great Lakes. We operate satellites, ships, and submersibles, as well as the world's only underwater habitat. To add a uniquely human dimension to ocean research and marine services, NOAA conducts wet diving operations throughout the Great Lakes, the territorial sea, the U.S. Exclusive Economic Zone, and wherever the agency is involved in marine operations and research.

NOAA numbers among its staff the largest diving complement of any civil Federal agency—more than 250 men and women. (This number does not include those civilian scientists, engineers, and technicians who dive under the auspices of NOAA-sponsored research grants, a factor that significantly increases that number.) As befits the variety of their missions, NOAA's divers are scientists, engineers, technicians, and officers in the NOAA Corps, and all have volunteered to be divers.

Because the tasks NOAA divers carry out are as varied as those of any group of underwater workers in the world, this version of the *NOAA Diving Manual*—greatly expanded and revised—contains instructions, recommendations, and general guidance on the broadest possible range of underwater living conditions and dive situations. Thus, while the *Manual* is directed toward NOAA, it will be useful, as were previous editions, to working divers who have other affiliations and to those who dive for pleasure only.

Under authority delegated by the Secretary of Commerce, NOAA takes seriously the mandate under Section 21(e) of the Outer Continental Shelf Lands Act Amendments of 1978 to "conduct studies of underwater diving techniques and equipment suitable for protection of human safety and improvement in diver performance . . . ." NOAA is proud of its record of safe diving and the assistance it has provided to the diving community.

To continue that record, the *Manual* has been revised to incorporate recommendations and information obtained from the entire diving community. The various issues addressed and the procedures recommended reflect the wisdom, experience, and specialized skills of working and recreational divers, equipment manufacturers, medical and scientific authorities, and many others.

Under ordinary circumstances, the guidance in this *Manual* could mean the difference between a successful mission and a failure. In an extreme situation, however, it could make the difference between life and death. To those who contributed to this revision, I express, on behalf of all of NOAA, my deep appreciation for their assistance in making this revision of the *Manual* a truly useful document for all divers.

John A. Knauss

Under Secretary of Commerce
for Oceans and Atmosphere

PREFACE

This *Manual* has been developed for use by NOAA divers. It focuses principally on diving to depths that are shallower than 250 feet (76 m), the depth range in which NOAA divers generally operate. Other sources should be referred to for information on deep-water mixed-gas diving procedures. As in previous versions, references have been used liberally to keep this *Manual* to a manageable size.

This version of the *Manual* contains many changes from the first and second editions. Immediately noticeable is the loose-leaf format, which will greatly facilitate revision and additions. This format will permit the *Manual* to be updated no matter how large or small the section needing revision, e.g., a section, a paragraph, or a single table. This edition of the *Manual* has 25 distinct parts: 20 sections and 5 appendixes. Of these units, 6 are new, 12 have undergone major revision, and 7 are largely unchanged, as noted below:

New:

Section 1	History of Diving
Section 11	Polluted-Water Diving
Section 13	Women and Diving
Appendix A	Diving With Disabilities
Appendix C	Treatment Flowchart and Recompression Treatment Tables
Appendix E	Glossary

Substantially revised:

Section 4	Compressed Air and Support Equipment
Section 5	Diver and Diving Equipment
Section 6	Hyperbaric Chambers and Support Equipment
Section 7	Diver and Support Personnel Training
Section 9	Procedures for Scientific Dives
Section 10	Diving Under Special Conditions
Section 14	Air Diving and Decompression
Section 15	Mixed Gas and Oxygen Diving
Section 18	Emergency Medical Care
Section 19	Accident Management and Emergency Procedures
Section 20	Diagnosis and Treatment of Diving Casualties
Appendix D	NOAA Nitrox I Diving and Decompression Tables

Largely unchanged:

Section 2	Physics of Diving
Section 3	Diving Physiology
Section 8	Working Dive Procedures
Section 12	Hazardous Aquatic Animals
Section 16	Saturation Diving
Section 17	Underwater Support Platforms
Appendix B	U.S. Navy Air Decompression Tables

Although the recommendations and guidelines contained in this *Manual* are based on the best information available, they are not intended to replace judgment and expert opinion or to restrict the application of science and technology that may become available in the future. NOAA also recognizes that some procedures may have to be modified under controlled experimental conditions to permit the advance of science. Because the information in this *Manual* reflects the thinking and experience of many specialists in the field of diving, procedural variations should be made only on the basis of expert advice.

As stated above, this *Manual* has been developed for NOAA's divers, whose missions are varied but whose chief responsibilities are the conduct of oceanic and Great Lakes research and the support of such research activities.

NOAA also recognizes that this *Manual* will be useful for others who dive because it contains a wealth of information on applied diving techniques and technology. The information in this *Manual*, however, should not be taken to reflect any endorsement or approbation on the part of NOAA or its Undersea Research Program for any products illustrated, nor can either accept any liability for damage resulting from the use of incorrect or incomplete information.

The multidisciplinary nature of underwater exploration and research is such that the assistance of numerous experts in diving-related specialties was essential to the preparation of this *Manual*. To gain an appreciation of the number of individuals involved in the task, the reader is referred to the list of contributors and reviewers for this and previous editions. Special thanks go to all of these contributors and reviewers, but particular gratitude is extended to: the NOAA Diving Safety Board for its review and comments; Dr. Morgan Wells for his very thorough editing, including checking of tables and example problem calculations throughout; Dr. James W. Miller for numerous helpful suggestions, but especially for accepting the task of producing the Glossary; Marthe Kent, whose persistence, knowledge, and attention to detail drove the entire process; and Marcia Collie, who had to translate everyone's handwritten notes to intelligible and intelligent prose, cross-check every draft through to galley and the final page proofs, and in general to see to production.

Comments on this *Manual* are welcome. They should be directed to:

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DIAGNOSIS AND TREATMENT OF DIVING CASUALTIES

SECTION 1
HISTORY OF DIVING

HISTORY OF DIVING 1

1.0 GENERAL

Divers have penetrated the oceans through the centuries for purposes identical to those of modern diving: to acquire food, search for treasure, carry out military operations, perform scientific research and exploration, and enjoy the aquatic environment. In a brief history of diving, Bachrach (1982) identified five principal periods in the history of diving, from free (or breath-hold) diving, to bell diving, surface support or helmet (hard hat) diving, scuba diving, and, finally, saturation diving. (Atmospheric diving, another diving mode, is discussed in Section 17.5.) All of these diving modes are still currently in use.

1.1 FREE (BREATH-HOLD) DIVING

Free diving, or breath-hold diving, is the earliest of all diving techniques, and it has played an historic role in the search for food and treasure. The Hae-Nyu and Ama pearl divers of Korea and Japan (Figure 1-1) are among the better-known breath-hold divers. In his book, *Half Mile Down*, Beebe (1934) reports finding several mother-of-pearl inlays in the course of conducting an archeological dig at a Mesopotamia site that dated back to 4500 B.C.; these shells must have been gathered by divers and then fashioned into inlays by artisans of the period. Beebe also describes the extensive use of pearl shells among people from other ancient cultures. The Emperor of China, for example, received an oyster pearl tribute around 2250 B.C. Free divers were also used in military operations, as the Greek historian Thucydides reports. According to Thucydides, divers participated in an Athenian attack on Syracuse in which the Athenian divers cut through underwater barriers that the Syracusans had built to obstruct and damage the Greek ships. Free or breath-hold divers sometimes used hollow reeds as breathing tubes, which allowed them to remain submerged for longer periods; this type of primitive snorkel was useful in military operations (Larson 1959).

Free diving continues to be a major diving method. World records were set in 1969 by a U.S. Navy diver, Robert Croft, who made a breath-hold dive to 247 feet (75 meters), a record broken in 1976 by a French diver, Jacques Mayol, who set the current world's breath-hold dive record at 325 feet (99 meters). Mayol grasped the bar of a weighted line to plunge to this depth and held his breath for 3 minutes and 39 seconds.

The obvious advantage of free diving as a work method (and as a recreational method) is its mobility and the freedom of the breath-hold diver to maneuver; the obvious disadvantage is that the air supply is necessarily limited to the amount of air the diver can take in and maintain in a single breath or can obtain by means of a snorkel-type reed or tube to the surface. The modern snorkel is an aid in breath-hold diving but is not used to provide a continuous supply of air, because on descent it fills with water that must then be exhaled on surfacing.

1.2 DIVING BELLS

The second principal historical mode of diving is bell diving. One of the earliest reports of the use of a device that enabled a diver to enter the water with some degree of protection and a supply of air involved the diving bell *Colimpha* used in Alexander the Great's descent in approximately 330 B.C., depicted by an Indian artist in a 1575 miniature (Figure 1-2). An account of this dive appeared in the 13th century French manuscript, *The True History of Alexander*. In his *Problemata*, Aristotle described diving systems in use in his time: "they contrive a means of respiration for divers, by means of a container sent down to them; naturally the container is not filled with water, but air, which constantly assists the submerged man."

In the 1000 years following this period, very few developments occurred in diving. It was not until 1535 that Guglielmo de Lorena developed a device that can be considered a true diving bell. Davis (1962) tells of a diver who worked for about an hour in a lake near Rome using de Lorena's diving apparatus, which rested on his shoulders and had much of its weight supported by slings. De Lorena's "bell" thus provided a finite but reliable air supply.

In 1691, the British astronomer Sir Edmund Halley (who was then Secretary of the Royal Society) built and patented a forerunner of the modern diving bell, which he later described in a report to the Society. As Sir Edmund described it, the bell was made of wood coated with lead, was approximately 60 cubic feet (1.7 cubic meters) in volume, and had glass at the top to allow light to enter; there was also a valve to

Figure 1-1
Breath-Hold Pearl Divers

Photos courtesy Suk Ki Hong

vent the air and a barrel to provide replenished air (Figure 1-3). In his history of diving, Davis (1962) suggests that Halley undoubtedly knew of a development reported by the French physicist Denis Papin, who in 1689 had proposed a plan (apparently the first) to provide air from the surface to a diving bell under pressure. Papin proposed to use force pumps or bellows to provide air and to maintain a constant pressure within the bell. Davis speculates that Halley's choice of the barrel rather than forced air method of replenishment may have reflected Halley's concern that Papin (who was also a Fellow of the Royal Society) would accuse him of stealing his concept. Halley's method was used for over a century until Smeaton introduced a successful forcing pump in 1788. In 1799, Smeaton dived with his "diving chests," which used a forcing pump to replenish the air supply (Larson 1959).

Diving bells continue to be used today as part of modern diving systems, providing a method of transporting divers to their work sites while under pressure and, once at the site, of supplying breathing gas while the diver works. Both modern-day open (or "wet") and closed bells are clearly the successors of these ancient systems.

1.3 HELMET (HARD-HAT) DIVING

Although these early diving bells provided some protection and an air supply, they limited the mobility of the diver. In the 17th and 18th centuries, a number of devices (usually made of leather) were developed to provide air to divers and to afford greater mobility. However, most of these devices were not successful, because they relied on long tubes from the surface to provide air to the diver and thus did not deal with the problem of equalizing pressure at depth.

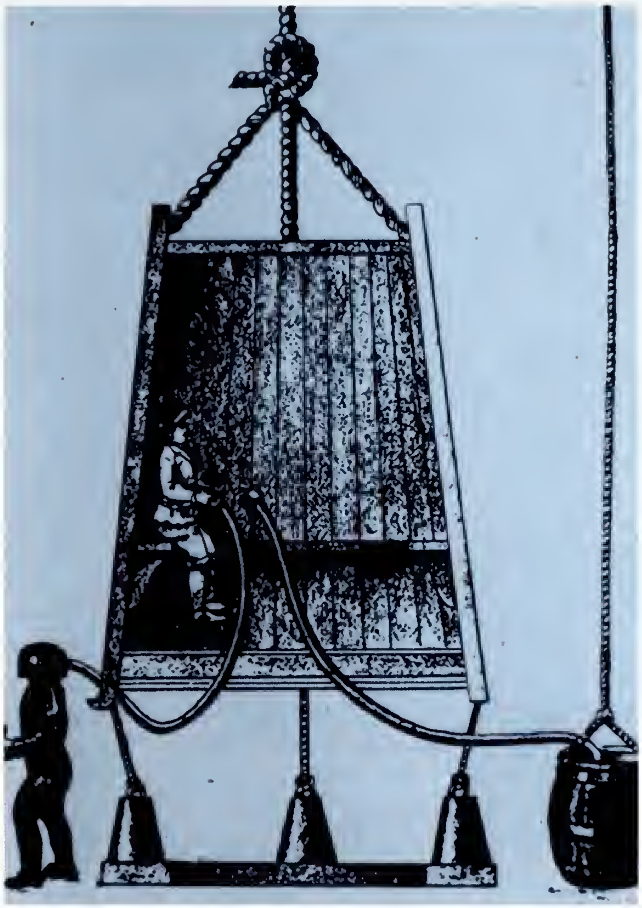
The first real step toward the development of a surface-supported diving technique occurred when the French scientist Freminet devised a system in which air was pumped from the surface with a bellows, allowing a constant flow of air to pass through a hose to the diver in the water. This system is considered by many to be the first true helmet-hose diving apparatus. Freminet has been credited with diving in 1774 with this device to a depth of 50 feet (15 meters), where he remained for a period of 1 hour.

The first major breakthrough in surface-support diving systems occurred with Augustus Siebe's invention of the diving dress in 1819. Around the same time,

Figure 1-2
Alexander the Great's Descent Into The Sea

Courtesy National Academy of Sciences

Figure 1-3
Halley's Diving Bell, 1690



Courtesy National Academy of Sciences

the Deane Brothers, John and Charles, were working on a design for a "smoke apparatus," a suit that would allow firefighters to work in a burning building.They received a patent for this system in 1823, and later modified it to "Deane's Patent Diving Dress," consisting of a protective suit equipped with a separate helmet with ports and hose connections for surface-supplied air. Siebe's diving dress consisted of a waist-length jacket with a metal helmet sealed to the collar. Divers received air under pressure from the surface by force pump; the air subsequently escaped freely at the diver's waist. In 1837, Siebe modified this open dress, which allowed the air to escape, into the closed type of dress. The closed suit retained the attached helmet but, by venting the air via a valve, provided the diver with a full-body air-tight suit. This suit served as the basis for modern hard-hat diving gear. Siebe's diving suit was tested and found to be successful in 1839 when the British started the salvage of the ship *Royal George*, which had sunk in 1782 to a depth of 65 feet (19.8 meters) (Larson 1959).

No major developments occurred in hard-hat gear until the 20th century, when mixed breathing gases, in particular helium-oxygen, were developed. The first major open-sea use of helium and oxygen as a breathing mixture occurred in the salvage of the submarine, the *USS Squalus*, in 1939. The breathing of mixed gases such as helium-oxygen permitted divers to dive to greater depths for longer periods than had been possible with air mixtures. The hard-hat surface-supported diving technique is probably still the most widely used commercial diving method; the use of heliox mixtures and the development of improved decompression tables have extended the diver's capability to work in this diving dress at depth. Although surface-supported diving has several advantages in terms of stability, air supply, and length of work period, a major problem with hard-hat gear is that it severely limits the diver's mobility. This limitation has been overcome in certain dive situations by the development of self-contained underwater breathing apparatus (scuba).

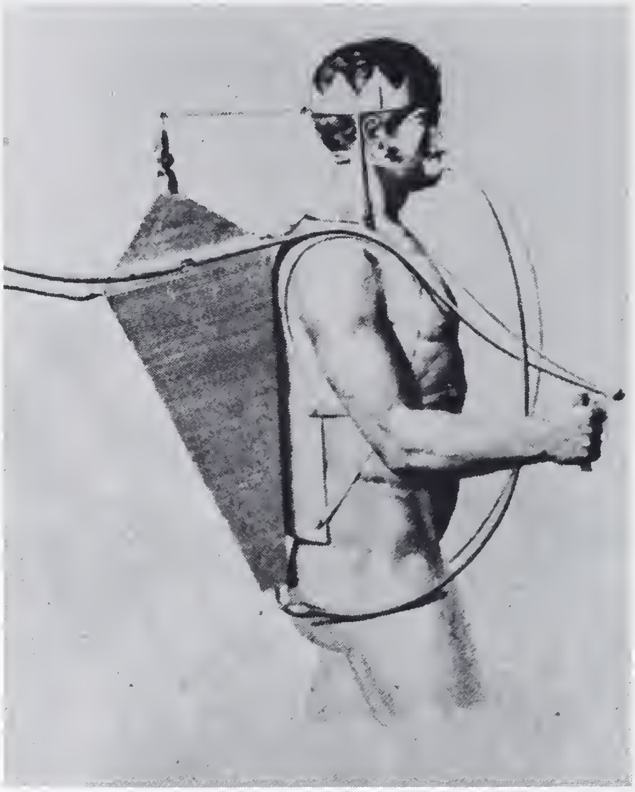
1.4 SCUBA DIVING

The development of self-contained underwater breathing apparatus provided the free moving diver with a portable air supply which, although finite in comparison with the unlimited air supply available to the helmet diver, allowed for mobility. Scuba diving is the most frequently used mode in recreational diving and, in various forms, is also widely used to perform underwater work for military, scientific, and commercial purposes.

There were many steps in the development of a successful self-contained underwater system. In 1808, Freiderich von Drieberg invented a bellows-in-a-box device (Figure 1-4) that was worn on the diver's back and delivered compressed air from the surface. This device, named *Triton*, did not actually work but it did serve to suggest that compressed air could be used in diving, an idea initially conceived of by Halley in 1716. In 1865, two French inventors, Rouquayrol and Denayrouse, developed a suit (Figure 1-5) that they described as "self-contained." In fact, their suit was not self contained but consisted of a helmet-using surface-supported system that had an air reservoir that was carried on the diver's back and was sufficient to provide one breathing cycle on demand. The demand valve regulator was used with surface supply largely because tanks of adequate strength were not then available to handle air at high pressure. This system's demand valve, which was automatically controlled, represented a major breakthrough because it permitted the diver to have a breath of air when needed in an emergency. The Rouquayrol and Denayrouse apparatus was described with remarkable accuracy in Jules Verne's classic, *Twenty Thousand Leagues Under The Sea*, which was written in 1869, only 4 years after the inventors had made their device public (Larson 1959).

The demand valve played a critical part in the later development of one form of scuba apparatus. However, since divers using scuba gear exhaled directly into the surrounding water, much air was wasted. One solution to this problem was advanced by Henry Fleuss, an English merchant seaman who invented a closed-circuit breathing apparatus in 1879 that used pure oxygen compressed to 450 psig for the breathing gas supply and caustic potash to purify the exhaled oxygen. Fleuss' "closed circuit oxygen-rebreather SCUBA" passed a crucial test when it was used successfully in 1880 by the English diver Alexander Lambert to enter a flooded tunnel beneath the Severn River to secure an iron door that had jammed open and to make needed repairs in the tunnel. Although Fleuss' rebreather was successful in this limited application, the depth limitations associated with the use of pure oxygen directed most attention to compressed air as a breathing mixture.

Figure 1-4
Triton Diving Apparatus



Courtesy National Academy of Sciences

In the 1920's, a French naval officer, Captain Yves Le Prieur, began work on a self-contained air diving apparatus that resulted in 1926 in the award of a patent, shared with his countryman Fernez. This device (Figure 1-6) was a steel cylinder containing compressed air that was worn on the diver's back and had an air hose connected to a mouthpiece; the diver wore a nose clip and air-tight goggles that undoubtedly were protective and an aid to vision but did not permit pressure equalization. The cylinder on the first Fernez-Le Prieur model contained around 2000 psi of air and permitted the wearer to remain less than 15 minutes in the water. Improved models later supplied sufficient air to permit the diver to remain for 30 minutes at 23 feet (7 meters) or 10 minutes at 40 feet (12 meters). The major problem with Le Prieur's apparatus was the lack of a demand valve, which necessitated a continuous flow (and thus waste) of gas. In 1943, almost 20 years after Fernez and Le Prieur patented their apparatus, two other French inventors, Emile Gagnan and Captain Jacques-Yves Cousteau, demonstrated their "Aqua Lung." This apparatus used a demand intake valve drawing from two or three cylinders, each containing over 2500 psig. Thus it was that the demand regulator, invented over 70 years earlier by Rouquayrol and Denayrouse and extensively used in aviation, came into use in a self-contained breathing apparatus that did not emit a wasteful flow of air during inhalation

Figure 1-5
Rouquayrol-Denayrouse Semi-Self-Contained Diving Suit

Courtesy National Academy of Sciences

(although it continued to lose exhaled gas into the water). This application made possible the development of modern open-circuit air scuba gear (Larson 1959).

In 1939, Dr. Christian Lambertsen began the development of a series of three patented forms of oxygen rebreathing equipment for neutral buoyancy underwater swimming, which became the first self-contained underwater breathing apparatus successfully used by a large number of divers. The Lambertsen Amphibious Respiratory Unit (LARU) (Figure 1-7) formed the basis for the establishment of U.S. military self-contained diving (Larson 1959).

This apparatus was designated scuba (for self-contained underwater breathing apparatus) by its users. Equivalent self-contained apparatus was used by the military forces of Italy, the United States, and Great Britain during World War II and continues in active use today. The rebreathing principle, which avoids waste of gas supply, has been extended to include forms of scuba that allow the use of mixed gas (nitrogen or helium-oxygen mixtures) to increase depth and duration beyond the practical limits of air or pure oxygen breathing (Larson 1959).

Figure 1-6
Fernez-Le Prieur Self-Contained Diving Apparatus

Courtesy National Academy of Sciences

A major development in regard to mobility in diving occurred in France during the 1930's: Commander de Carlieu developed a set of swim fins, the first to be produced since Borelli designed a pair of claw-like fins in 1680. When used with Le Prieur's tanks, goggles, and nose clip, de Carlieu's fins enabled divers to move horizontally through the water like true swimmers, instead of being lowered vertically in a diving bell or in hard-hat gear. The later use of a single-lens face mask, which allowed better visibility as well as pressure equalization, also increased the comfort and depth range of diving equipment.

Thus the development of scuba added a major working tool to the systems available to divers; the new mode allowed divers greater freedom of movement and access to greater depths for extended times and required much less burdensome support equipment. Scuba also enriched the world of sport diving by permitting recreational divers to go beyond goggles and breath-hold diving to more extended dives at greater depths.

Figure 1-7
World War II Military Swimmer Dressed in Lambertsen Amphibious Respiratory Unit

Courtesy C. J. Lambertsen

1.5 SATURATION DIVING

Although the development of surface-supplied diving permitted divers to spend a considerable amount of working time under water, divers using surface-supplied systems for deep and/or long dives incurred a substantial decompression obligation in the course of such dives. The initial development of saturation diving by the U.S. Navy in the late 1950's and its extension by naval, civilian government, university, and commercial laboratories revolutionized scientific, commercial, and military diving by providing a method that permits divers to remain at pressures equivalent to depths of up to 2000 feet (610 meters) for periods of weeks or months without incurring a proportional decompression obligation.

Saturation diving takes advantage of the fact that a diver's tissues become saturated once they have absorbed all the nitrogen or other inert gas they can hold at that particular depth; that is, they cannot absorb any additional gas. Once a diver's tissues are saturated, the diver can remain at the saturation depth (or a depth within an allowable excursion range up or down from the saturation depth) as long as necessary without proportionately increasing the amount of time required for decompression.

Divers operating in the saturation mode work out of a pressurized facility, such as a diving bell, seafloor habitat, or diver lockout submersible. These subsea facilities are maintained at the pressure of the depth at which the diver will be working; this depth is termed the saturation or storage depth.

The historical development of saturation diving depended both on technological and scientific advances. Engineers developed the technology essential to support the saturated diver, and physiologists and other scientists defined the respiratory and other physiological capabilities and limits of this mode. Many researchers played essential roles in the development of the saturation concept, but the U.S. Navy team working at the U.S. Submarine Medical Research Laboratory in New London, Connecticut, is generally given credit for making the major initial breakthroughs in this field. This team was led by two Navy diving medical officers, George Bond and Robert Workman, who, in the period from the mid-1950's to 1962, supervised the painstaking animal tests and volunteer human dives that provided the scientific evidence necessary to confirm the validity of the saturation concept (Lambertsen 1967).

1.5.1 Saturation Diving Systems

The earliest saturation dive performed in the open sea was conducted by the Link group and involved the use of a diving bell for diving and for decompression. Initial Navy efforts involved placing a saturation habitat on the seafloor. In 1964, Edwin Link, Christian Lambertsen, and James Lawrie developed the first deck decompression chamber, which allowed divers in a sealed bell to be locked into a pressurized environment at the surface for the slow decompression from saturation. The first commercial application of this form of saturation diving took place on the Smith Mountain Dam project in 1965 and involved the use of a personnel transfer capsule. The techniques pioneered at Smith Mountain have since become standard in commercial diving operations: saturated divers live, under pressure, in the deck decompression chamber on board a surface vessel and are then transferred to the underwater worksite in a pressurized personnel transfer chamber (also called a surface decompression chamber) (Lambertsen 1967). Although saturation diving systems are the most widely used saturation systems in commercial diving today, two other diving technologies also take advantage of the principle of saturation: habitats and lockout submersibles.

1.5.2 Habitats

Habitats are seafloor laboratory/living quarters in which saturated diver-scientists live and work under pressure for extended periods of time. Habitat divers dive from the surface and enter the habitat, or they may be compressed in a pressure vessel on the surface to the pressure of the habitat's storage depth and then be transferred to the habitat. Decompression may take place on the seafloor or in a surface decompression chamber after the completion of the divers' work. The most famous and widely used habitat was NOAA's *Hydrolab*, which was based in the Bahamas and Caribbean from 1972 to 1985 and provided a base for more than 600 researchers from 9 countries during that time. In 1985, the *Hydrolab* was retired from service and now resides permanently in the Smithsonian Institution's National Museum of Natural History in Washington, D.C. The *Aquarius*, a more flexible and technologically advanced habitat system, has replaced the *Hydrolab* as NOAA's principal seafloor research laboratory. (See Section 17 for a more detailed discussion of habitat-based in-situ research programs.)

1.5.3 Lockout Submersibles

Lockout submersibles provide an alternative method for diver/scientists to gain access to the underwater environment. Lockout submersibles are dual-purpose vehicles that permit the submersible's pilot/driver and crew to remain at surface pressure (i.e., at a pressure of 1 atmosphere), while the diver-scientist is pressurized in a separate compartment to the pressure of the depth at which he or she will be working. The lockout compartment thus serves in effect as a personnel transfer capsule, transporting the diver to and from the seafloor. The *Johnson Sea-Link*, which can be pressurized to 2000 fsw (610 msw), has played a central role in NOAA's undersea research program for years, particularly in pollution and fisheries research off the Atlantic coast.

1.6 SUMMARY

Humans have explored the ocean depths at least since the fifth millennium B.C., and the development of the diving techniques and systems described in this section reflects mankind's drive for mastery over all aspects of the environment. The search for methods that will allow humans to live comfortably in the marine biosphere for long periods of time continues today, as engineers and scientists work together to make access to the sea safer, easier, and more economical.

SECTION 2
PHYSICS OF DIVING

PHYSICS OF DIVING 2

2.0 GENERAL

This section describes the laws of physics as they affect humans in the water. A thorough understanding of the physical principles set forth in the following paragraphs is essential to safe and effective diving performance.

2.1 DEFINITIONS

This paragraph defines the basic principles necessary to an understanding of the underwater environment. The most important of these are listed below.

2.1.1 Pressure

Pressure is force acting on a unit area. Expressed mathematically:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \quad \text{or} \quad P = \frac{F}{A}$$

Pressure is usually expressed in pounds per square inch (psi) or kilograms per square centimeter (kg/cm^2).

2.1.2 Temperature

Heat is a form of energy that increases the temperature of the substance or matter to which it is added and decreases the temperature of the matter from which it is removed, providing that the matter does not change state during the process. Quantities of heat are measured in calories or British thermal units (Btu).

The temperature of a body is a measure of its heat. Temperature is produced by the average kinetic energy or speed of the body's molecules, and it is measured by a thermometer and expressed in degrees centigrade (°C) or Fahrenheit (°F). The quantity of heat in the body is equal to the total kinetic energy of all of its molecules.

Temperature values must be converted to absolute values for use with the Gas Laws. Both the Kelvin and Rankine scales are absolute temperature scales. Absolute zero is the hypothetical temperature characterized by the complete absence of heat; it is equivalent to approximately -273°C or -460°F. Conversion to the Kelvin or Rankine scales is done by adding 273 units to the temperature value expressed in centigrade or 460 units to the temperature value expressed in Fahrenheit, respectively.

Kelvin (K) = °C plus 273.15
Rankine (R) = °F plus 459.67

Temperatures measured in centigrade may be converted to Fahrenheit using the following formula:

$$^\circ F = (1.8 \times {^\circ C}) + 32$$

Temperatures measured in Fahrenheit may be converted to centigrade using the following formula:

$$^\circ C = \frac{(^\circ F - 32)}{1.8}$$

2.1.3 Density

Density is mass per unit volume. Expressed mathematically:

$$\text{Density (D)} = \frac{\text{Mass}}{\text{Volume}}$$

Density is usually stated in pounds per cubic foot (lb/ft^3) in the English system and in grams per cubic centimeter (gm/cm^3) in the metric system.

2.1.4 Specific Gravity

Specific gravity is the ratio of the density of a substance to the density of fresh water at 39.2°F (4°C). Fresh water has a specific gravity of 1.0 at 39.2°F (4°C); substances heavier than fresh water have specific gravities greater than 1.0, and substances lighter than fresh water have specific gravities less than 1.0. The human body has a specific gravity of approximately 1.0, although this varies slightly from one person to another.

2.1.5 Seawater

Seawater is known to contain at least 75 elements that occur in nature. The four most abundant elements in seawater are oxygen, hydrogen, chlorine, and sodium. Seawater is always slightly alkaline because it contains several alkaline earth minerals, principally sodium, calcium, magnesium, and potassium. The temperature of seawater varies from 30.2°F to 86.0°F (-1°C to 30°C).

The specific gravity of seawater is affected both by salinity and temperature, and these effects are interrelated. For example, water with a high enough salt content to sink toward the bottom will float at the surface if the water is sufficiently warm. Conversely, water with a relatively low salt content will sink if it is sufficiently chilled. Seawater also is an excellent electrical conductor, an interaction that causes corrosion problems when equipment is used in or near the ocean.

The viscosity of seawater varies inversely with temperature and is nearly twice as great at 33.8°F (1°C) as at 89.6°F (32°C). The impact of this property can be seen when the same sailboat is able to achieve higher speeds in warm water than in cold.

In many parts of the world the metric system of measurement is used rather than the English system still widely used in the United States. Table 2-1 presents factors for converting metric to English units.

Table 2-1
Conversion Factors, Metric to English Units

To Convert From Metric Units	To English Units	Multiply By
PRESSURE		
1 gm/cm^2	inch of fresh water	0.394
1 kg/cm^2	pounds/square inch (psi)	14.22
1 kg/cm^2	feet of fresh water (ffw)	32.8
1 kg/cm^2	inches of mercury (in. Hg)	28.96
1 cm Hg	pound/square inch	0.193
1 cm Hg	foot of fresh water	0.447
1 cm Hg	foot of seawater (fsw)	0.434
1 cm Hg	inch of mercury	0.394
1 cm of fresh water	inch of fresh water	0.394
VOLUME AND CAPACITY		
1 cc or ml	cubic inch (cu in.)	0.061
1 m^3	cubic feet (cu ft)	35.31
1 liter	cubic inches	61.02
1 liter	cubic foot	0.035
1 liter	fluid ounces (fl oz)	33.81
1 liter	quarts (qt)	1.057
WEIGHT		
1 gram	ounce (oz)	0.035
1 kg	ounces	35.27
1 kg	pounds (lb)	2.205
LENGTH		
1 cm	inch	0.394
1 meter	inches	39.37
1 meter	feet	3.28
1 km	mile	0.621
AREA		
1 cm^2	square inch	0.155
1 m^2	square feet	10.76
1 km^2	square mile	0.386

Adapted from NOAA (1979)

2.2 PRESSURE

The pressure on a diver under water is the result of two forces: the weight of the water over him or her and the weight of the atmosphere over the water. Table 2-2 provides factors for converting various barometric pressure units into other pressure units. The various types of pressure experienced by divers are discussed in the following sections.

2.2.1 Atmospheric Pressure

Atmospheric pressure acts on all bodies and structures in the atmosphere and is produced by the weight of atmospheric gases. Atmospheric pressure acts in all directions at any specific point. Since it is equal in all directions, its effects are usually neutralized. At sea level, atmospheric pressure is equal to 14.7 psi or 1.03 kg/cm^2. At higher elevations, this value decreases. Pressures above 14.7 psi (1.03 kg/cm^2) are often expressed in atmospheres. For example, one atmosphere is equal to 14.7 psi, 10 atmospheres is equal to 147 psi, and 100 atmospheres is equal to 1470 psi. Figure 2-1 shows equivalent pressures in the most commonly used units for measuring pressure at both altitude and depth.

2.2.2 Hydrostatic Pressure

Hydrostatic pressure is produced by the weight of water (or any fluid) and acts on all bodies and structures immersed in the water (or fluid). Like atmospheric pressure, hydrostatic pressure is equal in all directions at a specific depth. The most important form of pressure to divers is hydrostatic pressure. It increases at a rate of 0.445 psi per foot (1 kg/cm^2 per 9.75 meters) of descent in seawater and 0.432 psi per foot (1 kg/cm^2 per 10 meters) of descent in fresh water. This relationship is shown graphically in Figure 2-2.

2.2.3 Absolute Pressure

Absolute pressure is the sum of the atmospheric pressure and the hydrostatic pressure exerted on a

Table 2-2
Conversion Table for Barometric Pressure Units

		atm	N/m^2 or Pa	bars	mb	kg/cm^2	gm/cm^2 (cm H_2O)	mm Hg	in. Hg ("Hg)	lb/in^2 (psi)
1 atmosphere	=	1	$1.013X10^{5}$	1.013	1013	1.033	1033	760	29.92	14.70
1 Newton (N)/m^2 or Pascal (Pa)	=	$.9869X10^{-5}$	1	10^{-5}	.01	$1.02X10^{-5}$	.0102	.0075	$.2953X10^{-3}$	$.1451X10^{-3}$
1 bar	=	.9869	10^{5}	1	1000	1.02	1020	750.1	29.53	14.51
1 millibar (mb)	=	$.9869X10^{-3}$	100	.001	1	.00102	1.02	.7501	.02953	.01451
1 kg/cm^2	=	.9681	$.9807X10^{5}$	.9807	980.7	1	1000	735	28.94	14.22
1 gm/cm^2 (1 cm H_2O)	=	968.1	98.07	$.9807X10^{-3}$	.9807	.001	1	.735	.02894	.01422
1 mm Hg	=	.001316	133.3	.001333	1.333	.00136	1.36	1	.03937	.01934
1 in. Hg	=	.0334	3386	.03386	33.86	.03453	34.53	25.4	1	.4910
1 lb/in^2 (psi)	=	.06804	6895	.06895	68.95	.0703	70.3	51.70	2.035	1

Adapted from NOAA (1979)

submerged body. Absolute pressure is measured in pounds per square inch absolute (psia) or kilograms per square centimeter absolute (kg/cm^2 absolute).

2.2.4 Gauge Pressure

Gauge pressure is the difference between absolute pressure and a specific pressure being measured. Pressures are usually measured with gauges that are balanced to read zero at sea level when they are open to the air. Gauge pressure is therefore converted to absolute pressure by adding 14.7 if the dial reads in psi or 1.03 if the dial reads in kg/cm^2.

2.2.5 Partial Pressure

In a mixture of gases, the proportion of the total pressure contributed by a single gas in the mixture is called the *partial pressure.* The partial pressure contributed by a single gas is in direct proportion to its percentage of the total volume of the mixture (see Section 2.5.1).

2.3 BUOYANCY

Archimedes' Principle explains the nature of buoyancy.

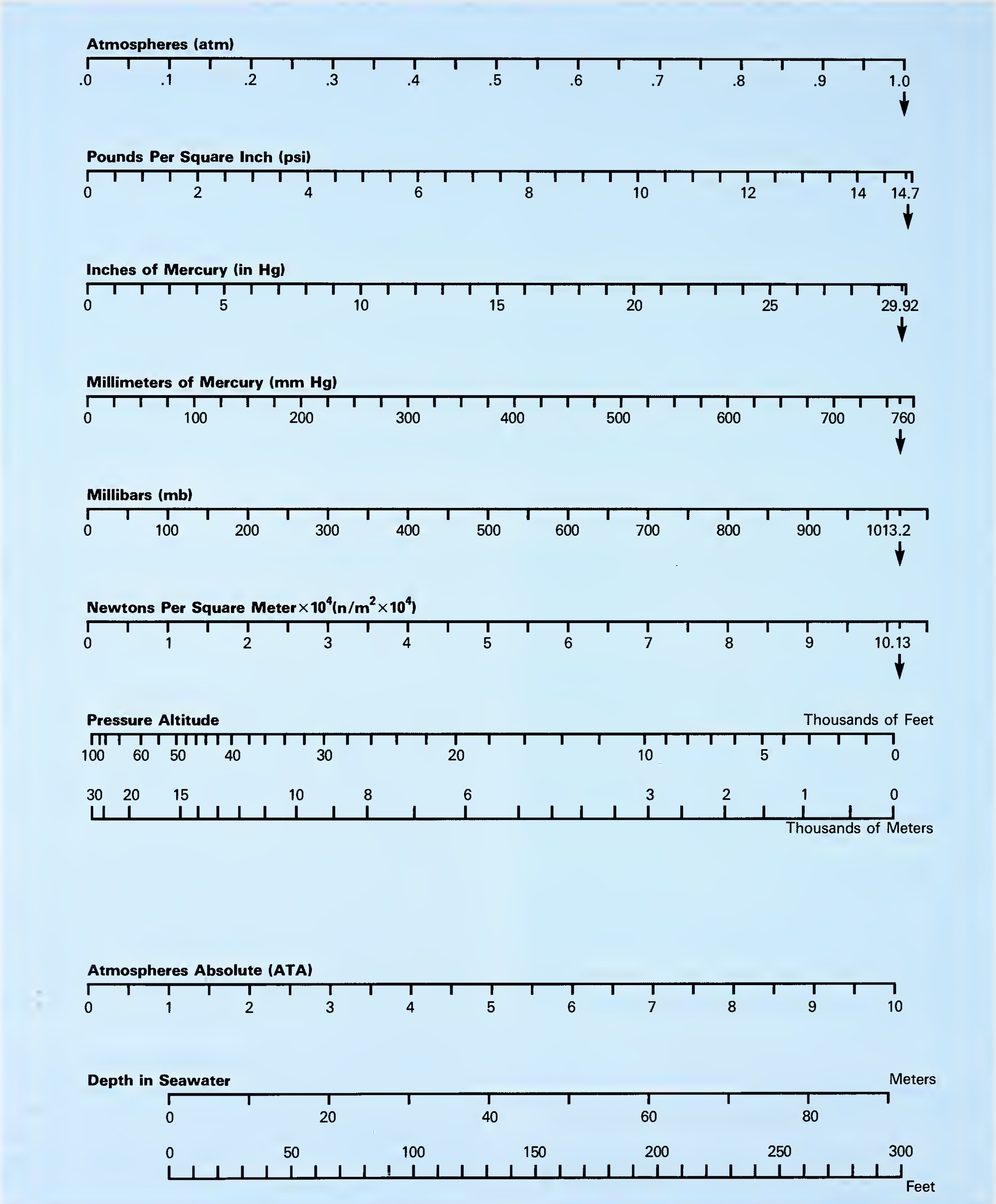
> A body immersed in a liquid, either wholly or partially, is buoyed up by a force equal to the weight of the liquid displaced by the body.

Using Archimedes' Principle, the buoyancy or buoyant force of a submerged body can be calculated by subtracting the weight of the submerged body from the weight of the displaced liquid. If the total displacement, that is, the weight of the displaced liquid, is greater than the weight of the submerged body, the buoyancy will be positive and the body will float or be buoyed upward. If the weight of the body is equal to that of the displaced liquid, the buoyancy will be neutral and the body will remain suspended in the liquid. If the weight of the submerged body is greater than that of the displaced liquid, the buoyancy will be negative and the body will sink.

The buoyant force of a liquid is dependent on its density, that is, its weight per unit volume. Fresh water has a density of 62.4 pounds per cubic foot (28.3 kg/0.03 m^3). Seawater is heavier, having a density of 64.0 pounds per cubic foot (29 kg/0.03 m^3). Therefore, a body in seawater will be buoyed up by a greater force than a body in fresh water, which accounts for the fact that it is easier to float in the ocean than in a fresh water lake.

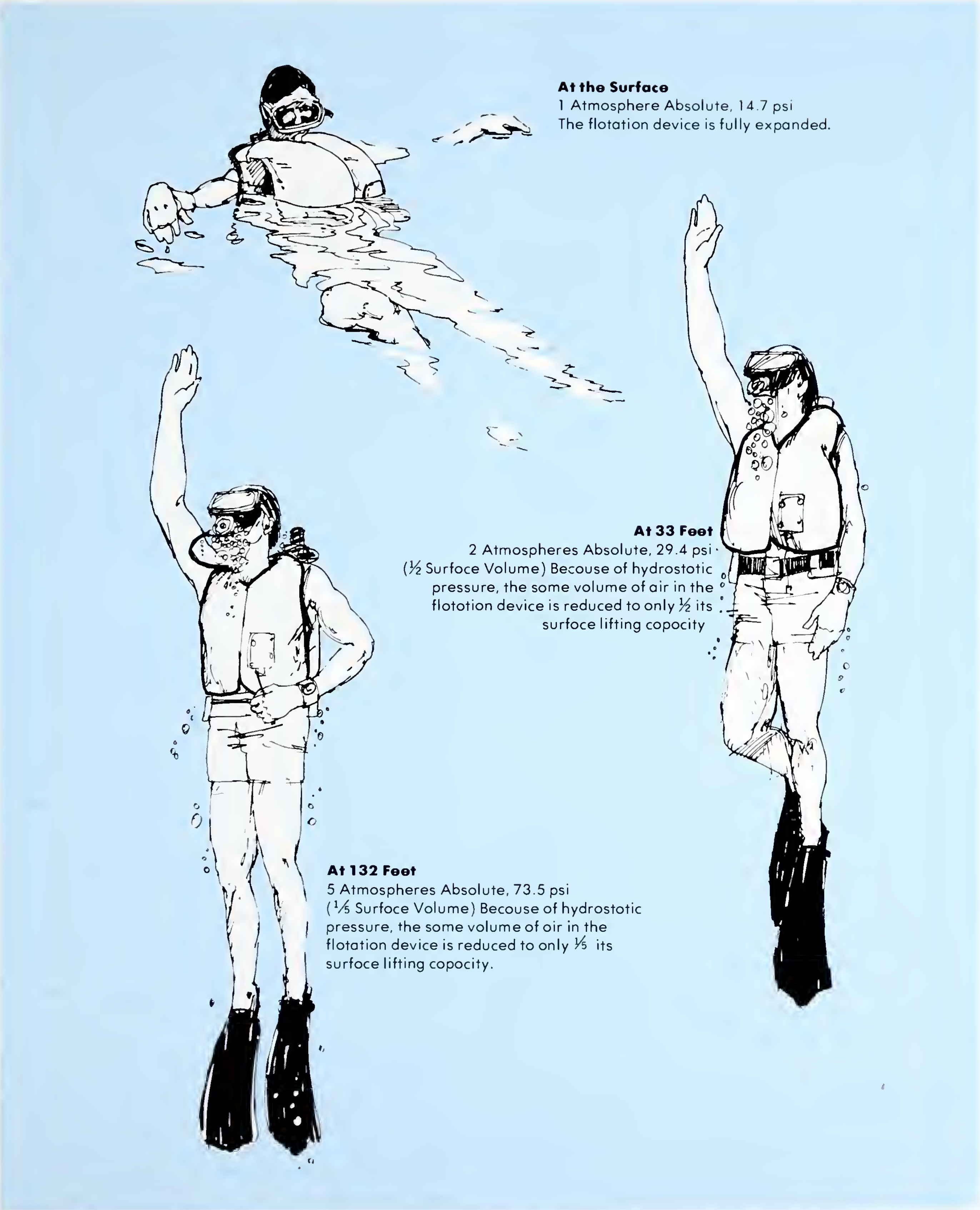
Lung capacity can have a significant effect on the buoyancy of a submerged person. A diver with full lungs displaces a greater volume of water and therefore is more buoyant than a diver with deflated lungs. Other individual differences that may affect buoyancy include bone structure, bone weight, and relative amount of body fat. These differences help to explain why certain individuals float easily and others do not.

Figure 2-1
Equivalent Pressures, Altitudes, and Depths



Adapted from National Aeronautics and Space Administration (1973)

Figure 2-2
Effects of Hydrostatic Pressure



At the Surface
1 Atmosphere Absolute, 14.7 psi
The flotation device is fully expanded.

At 33 Feet
2 Atmospheres Absolute, 29.4 psi
(½ Surface Volume) Because of hydrostatic pressure, the same volume of air in the flotation device is reduced to only ½ its surface lifting capacity

At 132 Feet
5 Atmospheres Absolute, 73.5 psi
(⅕ Surface Volume) Because of hydrostatic pressure, the same volume of air in the flotation device is reduced to only ⅕ its surface lifting capacity.

Adapted from NOAA (1979)

Divers wearing wet suits usually must add diving weights to their weight belts to provide the negative buoyancy that allows normal descent. At working depth, the diver should adjust his or her buoyancy to achieve a neutral state so that work can be accomplished without the additional physical effort of counteracting positive (upward) or negative (downward) buoyancy.

2.4 GASES USED IN DIVING

While under water, a diver is totally dependent on a supply of breathing gas. Two methods of providing breathing gases can be used. The diver may be supplied with gas via an umbilical from the surface or a submerged source, or he or she may carry the breathing gas supply. The second method is called scuba, an initialism for "**S**elf-**C**ontained **U**nderwater **B**reathing **A**pparatus."

Many combinations of breathing gases are used in diving. Compressed air is the most common, but the use of other mixtures for special diving situations is increasing. The following paragraphs describe the gases most commonly found in diving operations.

2.4.1 Air

Air is a mixture of gases (and vapors) containing nitrogen (78.084%), oxygen (20.946%), argon (0.934%), carbon dioxide (0.033%), and other gases (0.003%). Compressed air is the most commonly used breathing gas for diving (see Section 4).

2.4.2 Oxygen

Oxygen is a colorless, odorless, and tasteless gas that is only slightly soluble in water. It can be liquefied at -297.4°F (-183°C) at atmospheric pressure and will solidify when cooled to -361.1°F (-218.4°C). Oxygen is the only gas used by the human body, and it is essential to life. The other gases breathed from the atmosphere or breathed by divers in their gas mixtures serve only as vehicles and diluents for oxygen. However, oxygen is dangerous when excessive amounts are breathed under pressure; this harmful effect is called oxygen poisoning (see Section 3.3).

2.4.3 Nitrogen

Nitrogen is a colorless, odorless, and tasteless gas. It is chemically inert and is incapable of supporting life. Its boiling point is -320.8°F (-196°C). Nitrogen is commonly used as a diluent for oxygen in diving gas mixtures but has several disadvantages compared with some other diving gases. For example, when nitrogen is breathed at increased partial pressures, it has a distinct anesthetic effect called "nitrogen narcosis," a condition characterized by loss of judgment and disorientation (see Section 3.2.3.5).

2.4.4 Helium

Helium is found in the atmosphere only in trace amounts. It has the lowest boiling point of any known substance, -452.02°F (-268.9°C). Helium is colorless, odorless, and tasteless and is used extensively as a diluent for oxygen in deep diving gas mixtures. Helium has some disadvantages but none as serious as those associated with nitrogen. For example, breathing helium-oxygen mixtures causes a temporary distortion of speech (producing a Donald Duck-like voice), which hinders communication. Helium also has high thermal conductivity, which causes rapid loss of body heat in divers breathing a helium mixture. Helium is used in breathing mixtures at depth because of its lower density and lack of narcotic effect. However, helium should never be used in diving or treatment without a full understanding of its physiological implications.

2.4.5 Carbon Dioxide

Carbon dioxide (CO_2) is a gas produced by various natural processes such as animal metabolism, combustion, and fermentation. It is colorless, odorless, and tasteless. Although carbon dioxide generally is not considered poisonous, in excessive amounts it is harmful to divers and can even cause convulsions. Breathing CO_2 at increased partial pressure may cause unconsciousness (see Sections 3.1.3.2 and 20.4.1). For example, a person should not breathe air containing more than 0.10 percent CO_2 by volume (see Table 15-3); divers must therefore be concerned with the partial pressure of the carbon dioxide in their breathing gases. In the case of closed- and semi-closed-circuit breathing systems, the removal of the excess CO_2 generated by the diver's breathing is essential to diving safety (see Sections 15.5.1.2 and 15.5.1.3).

2.4.6 Carbon Monoxide

Carbon monoxide (CO) is a poisonous gas. It is colorless, odorless, and tasteless and therefore difficult to detect. Carbon monoxide is produced by the incomplete combustion of hydrocarbons, which occurs in the exhaust systems of internal combustion engines. Carbon monoxide may also be produced by over-heated oil-lubricated compressors. A level of 20 parts per million of CO should not be exceeded in pressurized breathing systems (see Table 15-3). When scuba cylinders are filled, care should be taken not to introduce CO from the exhaust system of the air compressor into the breathing gases. Proper precautions must be taken to ensure that all areas where cylinders are filled are adequately ventilated. The compressor's air intake must draw from an area where the atmosphere is free of contamination, such as automobile exhaust fumes.

2.4.7 Argon, Neon, Hydrogen

Argon, neon, and hydrogen have been used experimentally as diluents for oxygen in breathing gas mixtures, although these gases are not used routinely in diving operations. However, the results of recent research suggest that hydrogen-oxygen and helium-hydrogen-oxygen breathing mixtures may be used within the next decade in deep diving operations (Peter Edel, personal communication).

2.5 GAS LAWS

The behavior of all gases is affected by three factors: the temperature of the gas, the pressure of the gas, and the volume of the gas. The relationships among these three factors have been defined in what are called the Gas Laws. Five of these, Dalton's Law, Boyle's Law, Charles' Law, Henry's Law, and the General Gas Law, are of special importance to the diver.

2.5.1 Dalton's Law

Dalton's Law states:

> The total pressure exerted by a mixture of gases is equal to the sum of the pressures that would be exerted by each of the gases if it alone were present and occupied the total volume.

In a gas mixture, the portion of the total pressure contributed by a single gas is called the partial pressure of that gas. Stated mathematically:

$$P_{Total} = Pp_1 + Pp_2 + Pp_n$$

where

P_{Total} = total pressure of that gas

Pp_1 = partial pressure of gas component 1

Pp_2 = partial pressure of gas component 2

Pp_n = partial pressure of other gas components.

An easily understood example is that of a container at atmospheric pressure, 14.7 psi (1 kg/cm^2). If the container were filled with oxygen alone, the partial pressure of the oxygen would be 1 atmosphere. If the same container were filled with air, the partial pressures of each of the gases comprising air would contribute to the total pressure, as shown in the following tabulation:

Percent of Component × Total Pressure (Absolute) = Partial Pressure

Gas	Percent of component	Atmospheres partial pressure
N_2	78.08	0.7808
O_2	20.95	.2095
CO_2	.03	.0003
Other	.94	.0094
Total	100.00	1.0000

Example 1

If the same container, for example a scuba cylinder, were filled with air to 2000 psi, the following steps would be necessary to calculate the partial pressures (in ATA's) of the same components listed in the above table.

Step 1—Dalton's Law

Percent of component gas × total pressure (absolute) = partial pressure

Percent of components:

$$N_2 = \frac{78.08\%}{100} = .7808\ N_2$$

$$O_2 = \frac{20.95\%}{100} = .2095\ O_2$$

$$CO_2 = \frac{00.03\%}{100} = .0003\ CO_2$$

$$\text{Other} = \frac{00.94\%}{100} = .0094\ \text{Other}$$

Step 2—Convert 2000 psi to atmospheres absolute (ATA)

$$\frac{(2000\ \text{psi})}{14.7\ \text{psi}} + 1 = \text{ATA}$$

$$136 \quad + 1 = 137\ \text{ATA}$$

Step 3—Partial pressure of constituents at 137 ATA

$$Pp_{N_2} = 0.7808 \times 137 = 106.97 \text{ ATA}$$

$$Pp_{O_2} = 0.2095 \times 137 = 28.70 \text{ ATA}$$

$$Pp_{CO_2} = 0.0003 \times 137 = 0.04 \text{ ATA}$$

$$Pp_{Other} = 0.0094 \times 137 = 1.29 \text{ ATA}$$

Observe that the partial pressures of some components of the gas, particularly CO_2, increased significantly at higher pressures, although they were fairly low at atmospheric pressure. As these examples show, the implications of Dalton's Law are important and should be understood by all divers.

2.5.2 Boyle's Law

Boyle's Law states:

> At constant temperature, the volume of a gas varies inversely with absolute pressure, while the density of a gas varies directly with absolute pressure (Figure 2-3).

For any gas at a constant temperature, Boyle's Law is:

$$PV = K$$

where

P = absolute pressure
V = volume
K = constant.

Boyle's Law is important to divers because it relates changes in the volume of a gas to changes in pressure (depth) and defines the relationship between pressure and volume in breathing gas supplies. The following example illustrates Boyle's Law.

Example 1 (Boyle's Law)

An open diving bell with a volume of 24 cubic feet is to be lowered into the sea from a surface support ship. No air is supplied to or lost from the bell, and the temperature is the same at all depths. Calculate the volume of the air space in the bell at the 33-foot, 66-foot, and 99-foot depths.

Step 1—Boyle's Law (at surface):

$$P_1V_1 = K$$

P_1 = pressure at surface in ATA
V_1 = volume at surface in ft^3
K = constant.

Step 2—Boyle's Law (at 33 feet of water):

$$P_2V_2 = K$$

P_2 = pressure at 33 feet in ATA
V_2 = volume at 33 feet in ft^3
K = constant.

Step 3—Equating the constant, K, at the surface and at 33 feet, we have the following equation:

$$P_1V_1 = P_2V_2$$

Transposing to determine the volume at 33 feet:

$$V_2 = \frac{P_1V_1}{P_2}$$

where

P_1 = 1 atmosphere (ATA)
P_2 = 2 ATA
V_1 = 24 ft^3

$$V_2 = \frac{1 \text{ ATA} \times 24 \text{ ft}^3}{2 \text{ ATA}}$$

V_2 = 12 ft^3 .

Note that the volume of air in the open bell has been compressed from 24 to 12 cubic feet in the first 33 feet of seawater.

Step 4—Using the method illustrated above to determine the air volume at 66 feet:

$$V_3 = \frac{P_1V_1}{P_3}$$

where

P_3 = 3 ATA

$$V_3 = \frac{1 \text{ ATA} \times 24 \text{ ft}^3}{3 \text{ ATA}}$$

V_3 = 8 ft^3 .

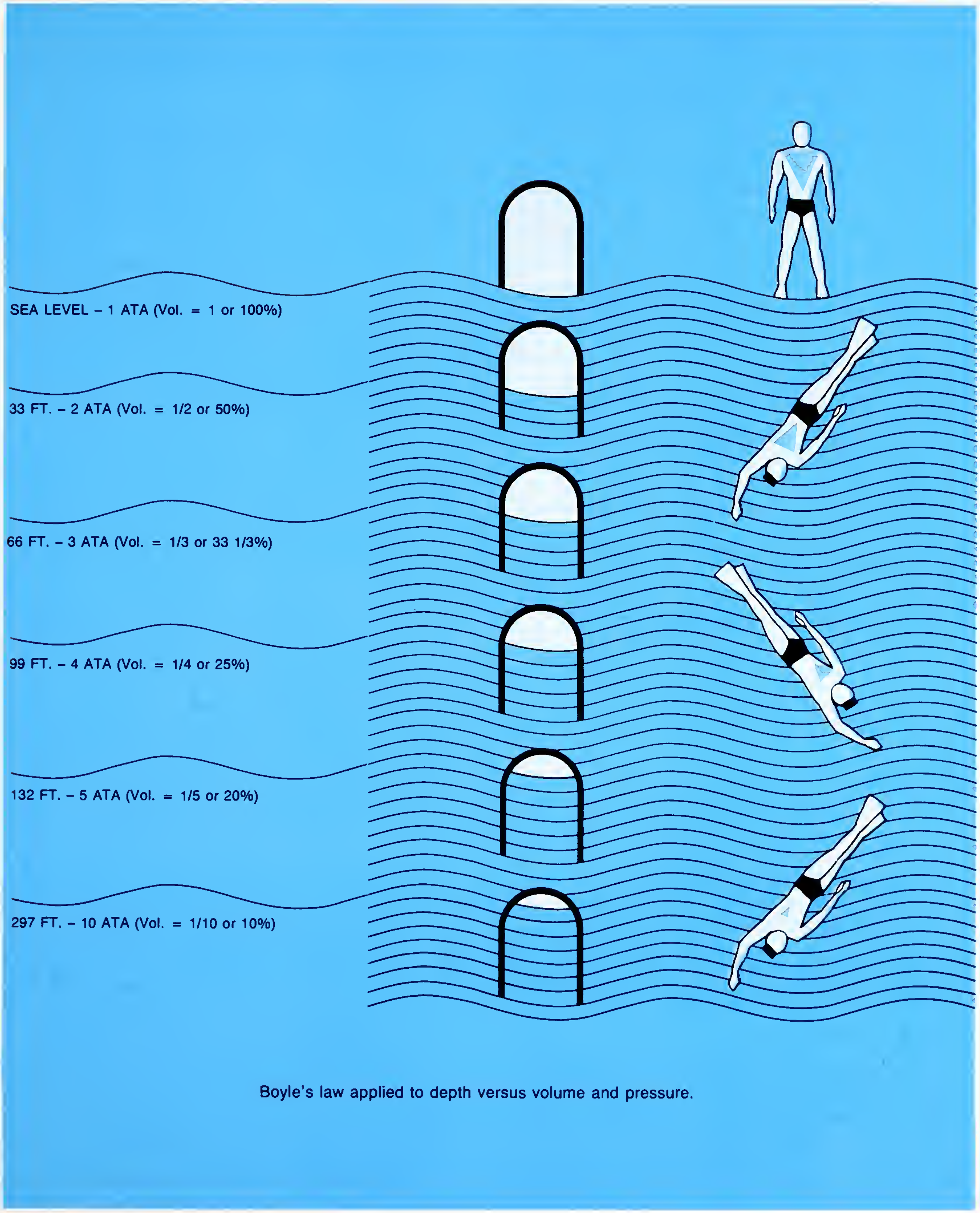
Step 5—For a 99-foot depth, using the method illustrated previously, the air volume would be:

$$V_4 = \frac{P_1V_1}{P_4}$$

where

P_4 = 4 ATA
V_4 = 6 ft^3 .

Figure 2-3
Boyle's Law



Boyle's law applied to depth versus volume and pressure.

Adapted from NOAA (1979)

As depth increased from the surface to 99 feet, the volume of air in the open bell was compressed from 24 cubic feet to 6 cubic feet.

In this example of Boyle's Law, the temperature of the gas was considered a constant value. However, temperature significantly affects the pressure and volume of a gas; it is therefore essential to have a method of including this effect in calculations of pressure and volume. To a diver, knowing the effect of temperature is essential, because the temperature of the water deep in the oceans or in lakes is often significantly different from the temperature of the air at the surface. The gas law that describes the physical effects of temperature on pressure and volume is Charles' Law.

2.5.3 Charles' Law

Charles' Law states:

> At a constant pressure, the volume of a gas varies directly with absolute temperature. For any gas at a constant volume, the pressure of a gas varies directly with absolute temperature.

Stated mathematically:

$$\frac{P_1}{P_2} = \frac{T_1}{T_2} \text{ (volume constant)}$$

$$\frac{V_1}{V_2} = \frac{T_1}{T_2} \text{ (pressure constant)}$$

where

P_1 = initial pressure (absolute)
P_2 = final pressure (absolute)
T_1 = initial pressure (absolute)
T_2 = final pressure (absolute)
V_1 = initial volume
V_2 = final volume.

To illustrate Charles' Law, an example similar to the one given for Boyle's Law can be used.

Example 2 (Charles' Law)

A closed diving bell at atmospheric pressure and having a capacity of 24 cubic feet is lowered from the surface to a depth of 99 feet in the ocean. At the surface, the temperature is 80°F; at 99 feet, the temperature is 33°F. Calculate the pressure on the bell when it is at the 99-foot level and the temperature is 33°F.

Because the volume of the closed bell is the same at the surface as it is at 99 feet, the decrease in the pressure is a result of the change in temperature. Therefore, using Charles' Law:

$$\frac{P_1}{P_2} = \frac{T_1}{T_2} \text{ (volume constant)}$$

where

P_1 = 14.7 psia (atmospheric pressure)
T_1 = 80°F + 460°F = 540 Rankine
T_2 = 33°F + 460°F = 493 Rankine.

Transposing:

$$P_2 = \frac{P_1 T_2}{T_1}$$

$$P_2 = \frac{14.7 \times 493}{540}$$

$$P_2 = 13.42 \text{ psia.}$$

Note that the final pressure is below atmospheric pressure (14.7 psia) because of the drop in temperature.

Example 3 (Charles' Law)

To illustrate Charles' Law further, consider the following example:

An open diving bell having a capacity of 24 cubic feet is lowered into the ocean to a depth of 99 feet. At the surface, the temperature is 80°F; at depth, the temperature is 45°F. What is the volume of the gas in the bell at 99 feet?

From Example 1 illustrating Boyle's Law, we know that the volume of the gas was compressed to 6 cubic feet when the bell was lowered to the 99-foot level. Applying Charles' Law then illustrates the additional reduction in volume caused by temperature effects:

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

where

V_1 = volume at depth, 6 ft^3
T_1 = 80°F + 460°F = 540 Rankine
T_2 = 45°F + 460°F = 505 Rankine.

Transposing:

$$V_2 = \frac{V_1T_2}{T_1}$$

$$V_2 = \frac{6 \times 505}{540}$$

$$V_2 = 5.61 \text{ ft}^3 .$$

2.5.4 Henry's Law

Henry's Law states:

> The amount of any given gas that will dissolve in a liquid at a given temperature is a function of the partial pressure of the gas that is in contact with the liquid and the solubility coefficient of the gas in the particular liquid.

This law simply states that, because a large percentage of the human body is water, more gas will dissolve into the blood and body tissues as depth increases, until the point of saturation is reached. Depending on the gas, saturation takes from 8 to 24 hours or longer. As long as the pressure is maintained, and regardless of the quantity of gas that has dissolved into the diver's tissues, the gas will remain in solution.

A simple example of the way in which Henry's Law works can be seen when a bottle of carbonated soda is opened. Opening the container releases the pressure suddenly, causing the gases in solution to come out of solution and to form bubbles. This is similar to what happens in a diver's tissues if the prescribed ascent rate is exceeded. The significance of this phenomenon for divers is developed fully in the discussion of decompression (see Section 3.2.3.2).

The formula for Henry's Law is:

$$\frac{VG}{VL} = \alpha P_1$$

where

VG = volume of gas dissolved at STP (standard temperature and pressure)

VL = volume of the liquid

α = Bunson solubility coefficient at specified temperatures

P_1 = partial pressure in atmospheres of that gas above the liquid.

2.5.5 The General Gas Law

Boyle's and Charles' laws can be conveniently combined into what is known as the General Gas Law, expressed mathematically as follows:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

where

P_1 = initial pressure (absolute)
V_1 = initial volume
T_1 = initial temperature (absolute)

and

P_2 = final pressure (absolute)
V_2 = final volume
T_2 = final temperature (absolute).

Example 4 (General Gas Law)

Let us again consider an open diving bell having a capacity of 24 cubic feet that is being lowered to 99 feet in seawater from a surface temperature of 80°F to a depth temperature of 45°F. Determine the volume of the gas in the bell at depth.

The General Gas Law states:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

where

$P_1 = 14.7$ psia
$V_1 = 24 \text{ ft}^3$
$T_1 = 80^\circ F + 460^\circ F = 540$ Rankine
$P_2 = 58.8$ psia
$T_2 = 45^\circ F + 460^\circ F = 505$ Rankine.

Transposing:

$$V_2 = \frac{P_1V_1T_2}{T_1P_2}$$

$$V_2 = \frac{(14.7)(24)(505)}{(540)(58.8)}$$

$$V_2 = 5.61 \text{ ft}^3 .$$

This is the same answer as that derived from a combination of Example 1 and Example 3, which were used to demonstrate Boyle's and Charles' Laws. Figure 2-4 illustrates the interrelationships among Boyle's Law, Charles' Law, and the General Gas Law.

2.6 GAS FLOW (VISCOSITY)

There are occasions when it is desirable to determine the rate at which gas flows through orifices, hoses, and other limiting enclosures. This can be approximated for a given gas by employing Poiseuille's equation for gases, which is expressed mathematically as:

$$V = \frac{\Delta P r^4 \pi}{8 L \eta}$$

where

V = gas flow, in $cm^3 \cdot sec^{-1}$

ΔP = pressure gradient between 2 ends of tube, in $dynes \cdot cm^{-2}$

r = radius of tube, in cm

L = length of tube, in cm

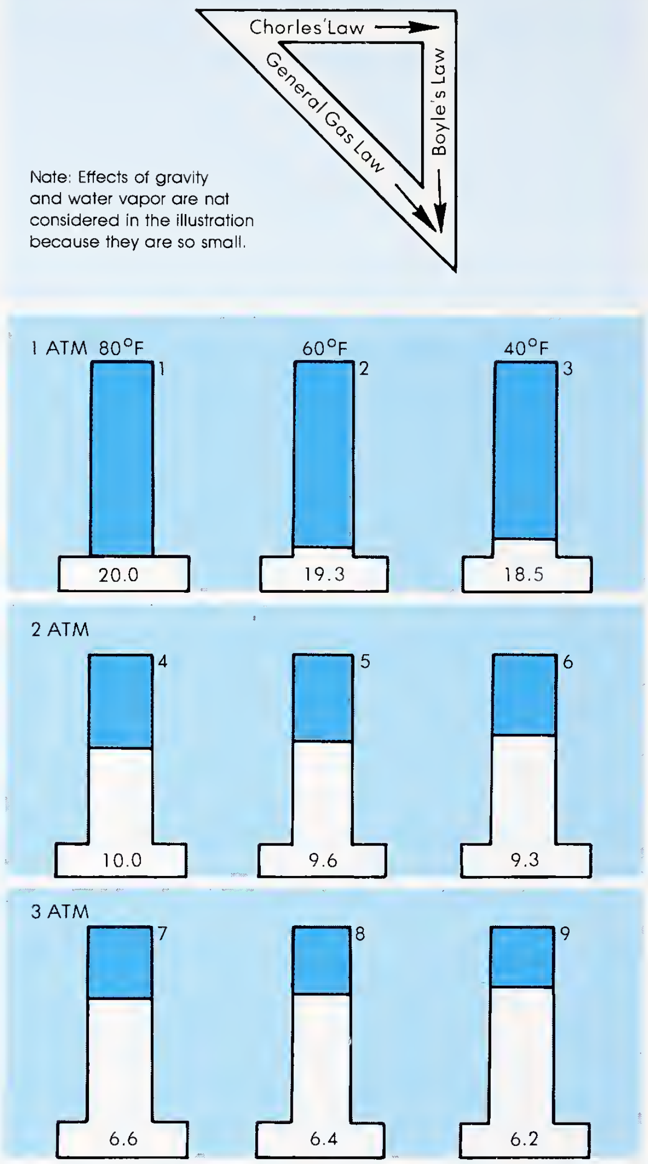
η = viscosity, in poise.

This equation can be used only in relatively simple systems that involve laminar flow and do not include a number of valves or restrictions. For practical applications, the diver should note that, as resistance increases, flow decreases in direct proportion. Therefore, if the length of a line is increased, the pressure must be increased to maintain the same flow. Nomograms for flow resistance through diving hoses can be found in Volume 2 of the *US Navy Diving Manual* (1987).

2.7 MOISTURE IN BREATHING GAS

Breathing gas must have sufficient moisture to be comfortable for the diver to breathe. Too much moisture in a system can increase breathing resistance and produce congestion; too little can cause an uncomfortable sensation of dehydration in the diver's mouth, throat, nasal passages, and sinus cavities (U.S. Navy 1988). Air or other breathing gases supplied from surface compressors or tanks can be assumed to be dry. This dryness can be reduced by removing the mouthpiece and rinsing the mouth with water or by having the diver introduce a small amount of water into his or her throat inside a full face mask. The use of gum or candy

Figure 2-4
Gas Laws



Note: Effects of gravity and water vapor are not considered in the illustration because they are so small.

Instructions:

(1) A uniform bore sealed-end tube with 20 divisions is inverted in a container of water at 80 degrees F and one atmosphere pressure. The conditions of temperature and pressure are then changed as illustrated to explain the three gas laws.

(2) Steps 1,2,3; 4,5,6; 7,8,9 (horizontally) illustrate Charles' Law, i.e., the reduction of volume with reduction in temperature at a constant pressure.

(3) Steps 1,4,7; 2,5,8; 3,6,9 (vertically) illustrate Boyle's Law, i.e., at a constant temperature the volume is inversely related to the pressure.

(4) Steps 1,5,9; 3,5,7 (diagonally) illustrate the General Gas Law i.e., a combination of Charles's and Boyle's Laws.

Adapted from NOAA (1979)

to reduce dryness while diving can be dangerous, because these items may become lodged in the diver's throat. The mouthpiece should not be removed in water that may be polluted (see Section 11).

2.7.1 Condensation in Breathing Tubes or Mask

Expired gas contains moisture that may condense in the breathing tubes or mask. This water is easily blown out through the exhaust valve and generally presents no problem. However, in very cold water the condensate may freeze; if this freezing becomes serious enough to block the regulator mechanism, the dive should be aborted.

2.7.2 Fogging of the Mask

Condensation of expired moisture or evaporation from the skin may cause fogging of the face mask glass. Moistening the glass with saliva, liquid soap, or commercially available anti-fog compounds will reduce or prevent this difficulty. However, it should be noted that some of the ingredients in chemical defogging agents can cause keratitis (inflammation of the cornea) if improperly used. Wright (1982) has described two such cases; symptoms included severe burning, photophobia, tearing, and loss of vision, which Wright attributed to the use of excessive quantities of the defogging solution and inadequate rinsing of the mask.

2.8 LIGHT AND VISION UNDER WATER

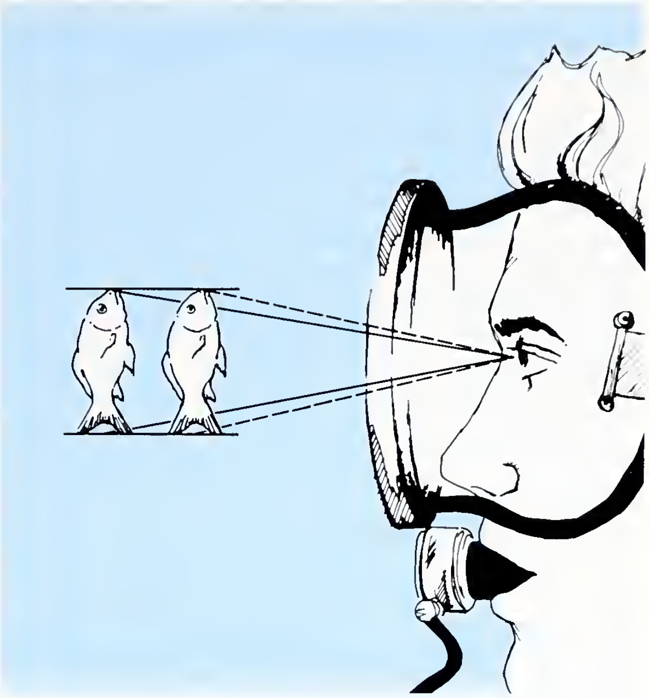
2.8.1 The Physics of Light Under Water and the Consequences for Vision

To function effectively under water, divers must understand the changes that occur in their visual perception under water. Many of these changes are caused simply by the fact that light, the stimulus for vision, travels through water rather than air; consequently it is refracted, absorbed, and scattered differently than in air. Refraction, absorption, and scatter all follow physical laws and their effects on light can be predicted; this changed physical stimulus can in turn have pronounced effects on our perception of the underwater world. Both the physical changes and their effects on vision are described in detail in Kinney (1985) and are only summarized here.

2.8.1.1 Refraction

In refraction, the light rays are bent as they pass from one medium to another of different density. In diving, the refraction occurs at the interface between the air in the diver's mask and the water. The refracted image of an underwater object (see Figure 2-5) is magnified, appears larger than the real image, and seems to be positioned at a point three-fourths of the actual distance between the object and the diver's faceplate.

Figure 2-5
Objects Under Water Appear Closer



Rays passing from water into air are refracted away from the normal, since the refractive index of water is 1.33 times that of air. The lens system of the eye (omitted for simplicity) forms a real inverted image on the retina, corresponding to that of an object at about three-quarters of its physical distance from the air-water interface. The angle subtended by the image is thus 4/3 larger than in air.

Source: NOAA (1979)

This displacement of the optical image might be expected to cause objects to appear closer to the diver than they actually are and, under some conditions, objects do indeed appear to be located at a point three-fourths of their actual distance from the diver. This distortion interferes with hand-eye coordination and accounts for the difficulty often experienced by novice divers attempting to grasp objects under water. At greater distances, however, this phenomenon may reverse itself, with distant objects appearing farther away than they actually are. The clarity of the water has a profound influence on judgments of depth: the more turbid the water, the shorter the distance at which the reversal from underestimation to overestimation occurs (Ferris 1972). For example, in highly turbid water, the distance of objects at 3 or 4 feet (0.9 or 1.2 m) may be *over*estimated; in moderately turbid water, the change might occur at 20 to 25 feet (6.1 to 7.6 m); and in very clear water, objects as far away as 50 to 75 feet (15.2 to 22.9 m) might be *under*estimated.

It is important for the diver to realize that judgments of depth and distance are probably inaccurate. As a rough rule of thumb, the closer the object, the more likely it will appear too close, and the more turbid the water, the greater the tendency to see it as too far away. Training to overcome inaccurate distance judgments can be effective, but it is important that it be carried out in water similar to that of the proposed dive or in a variety of different types of water (Ferris 1973). In addition, training must be repeated periodically to be effective.

Changes in the optical image result in a number of other distortions in visual perception. Mistakes in estimates of size and shape occur. In general, objects under water appear to be larger by about 33 percent than they actually are. This often is a cause of disappointment to sport divers, who find, after bringing catches to the surface, that they are smaller than they appeared under water. Since refraction effects are greater for objects off to the side of the field of view, distortion in the perceived shape of objects is frequent. Similarly, the perception of speed can be influenced by these distortions; if an object appears to cross the field of view, its speed will be increased because of the greater apparent distance it travels (Ross and Rejman 1972).

These errors in visual perception and misinterpretations of size, distance, shape, and speed caused by refraction can be overcome, to some extent, with experience and training. In general, experienced divers make fewer errors in judging the underwater world than do novice divers. However, almost all divers are influenced to some extent by the optical image, and attempts to train them to respond more accurately have met with some, but not complete, success.

Although the refraction that occurs between the water and the air in the diver's face mask produces these undesirable effects, air itself is essential for vision. For example, if the face mask is lost, the diver's eyes are immersed in water, which has about the same refractive index as the eyes. Consequently, no normal focusing of light occurs and the diver's vision is impaired immensely. The major deterioration is in visual acuity; other visual functions such as the perception of size and distance are not degraded as long as the object can be seen (Luria and Kinney 1974). The loss of acuity, however, is dramatic, and acuity may fall to a level that would be classified as legally blind (generally 20/200) on the surface (Luria and Kinney 1969). While myopes (near-sighted individuals) do not suffer quite as much loss in acuity if their face masks are lost as individuals with 20/20 vision do, the average acuities of the two groups, myopes and normals, were found to be 20/2372 and 20/4396, respectively, in one study of underwater acuity without a mask (Cramer 1975).

2.8.1.2 Scatter

Scatter occurs when individual photons of light are deflected or diverted when they encounter suspended particles in the water. Although scattering also occurs in air, it is of much greater concern under water because light is diffused and scattered by the water molecules themselves, by all kinds of particulate matter held in suspension in the water, and by transparent biological organisms. Normally, scatter interferes with vision and underwater photography because it reduces the contrast between the object and its background. This loss of contrast is the major reason why vision is so much more restricted in water than in air (Duntley 1963, Jerlov 1976); it also accounts for the fact that even large objects can be invisible at short viewing distances. In addition, acuity or perception of small details is generally much poorer in water than in air, despite the fact that the optical image of an object under water is magnified by refraction (Baddeley 1968). The deterioration increases greatly with the distance the light travels through the water, largely because the image-forming light is further interfered with as it passes through the nearly transparent bodies of the biomass, which is composed of organisms ranging from bacteria to jellyfish (Duntley 1976).

2.8.1.3 Absorption

Light is absorbed as it passes through the water, and much of it is lost in the process. In addition, the spectral components of light, the wavelengths that give rise to our perception of color, are differentially absorbed. Transmission of light through air does not appreciably change its spectral composition, but transmitting light through water, even through the clearest water, does, and this can change the resulting color appearance beyond recognition. In clearest water, long wavelength or red light is lost first, being absorbed at relatively shallow depths. Orange is filtered out next, followed by yellow, green, and then blue. Other waters, particularly coastal waters, contain silt, decomposing plant and animal material, and plankton and a variety of possible pollutants, which add their specific absorptions to that of the water. Plankton, for example, absorb violets and blues, the colors transmitted best by clear water. The amount of material suspended in some harbor water is frequently sufficient to alter the transmission curve completely; not only is very little light transmitted, but the long wavelengths may be transmitted better than the short, a complete reversal of the situation in clear water (Jerlov 1976, Kinney et al. 1967, Mertens 1970).

Color vision under water, whether for the visibility of colors, color appearances, or legibility, is thus much more complicated than in air. Accurate underwater color vision requires that divers know the colors involved, understand the sensitivity of the eye to different colors, know the depth and underwater viewing distance, and are familiar with the general nature of water and the characteristics of the specific waters involved. Information is available from several investigations about which colors can be seen best and which will be invisible under water (Kinney et al. 1967, 1969; Kinney and Miller 1974; Luria and Kinney 1974; Kinney 1985). Table 2-3 is a summary of the results of these experiments and shows the colors that were most visible when viewed by a diver against a water background.

Changes occur too in the appearance of colors under water. For example, red objects frequently appear black under water. This is readily understandable when one considers that red objects appear red on the surface because of reflected red light. Since clear water absorbs the red light preferentially, at depth no red light reaches the object to be reflected, and therefore the object appears unlighted or black. In the same way, a blue object in yellowish-green water near the coast could appear black. Substances that have more than one peak in their reflectance curve may appear quite different on land and in the sea. Blood is a good example; at the surface a reflectance maximum in the green is not noticeable because there is a much larger one in the red. At depth, the water may absorb the long wavelength light and blood may appear green. The ghostly appearance of divers in 20 to 30 feet (6.1 to 9.1 m) of clear water is another example of the loss of red light.

In general, less and less color is perceived as the depth and viewing distance under water are increased, and all objects tend to look as though they are the same color (the color that is best transmitted by that particular body of water). Objects must then be distinguished by their relative brightness or darkness. In Table 2-3, many of the most visible colors are light, bright colors that give good brightness contrast with the dark water background. If the background were different (for example, if it were white sand), darker colors would have increased visibility. Fluorescent colors are conspicuous under water because fluorescent materials convert short wavelength light into long wavelength colors that are rarely present under water, which increases the color contrast.

The use of color coding under water is complicated by these changes in color appearance, and only a few colors can be employed without risk of confusion. Green and orange are good choices, since they are not confused in any type of water. Another practical question concerns the most legible color for viewing instruments under water; the answer depends on many conditions, which are specified in *Human Engineering Guidelines for Underwater Applications* (Vaughan and Kinney 1980, 1981). In clear ocean water, most colors are equally visible if they are equally bright, but in highly turbid harbor waters, red is best for direct viewing and green is best for peripheral or off-center viewing.

2.8.1.4 Insufficient Light

Attenuation and scatter dramatically reduce the amount of natural light available under water, restricting natural daylight vision to a few hundred feet under the best of conditions and to 1 to 2 feet (0.30 to 0.61 m) or less under the worst or highly turbid conditions. If there is not enough light (without an auxiliary dive light) for daylight vision, many visual capabilities that we take for granted in air will be greatly different; this includes good acuity, color vision, and good central or direct vision. In a low-light situation, acuity is very poor and the diver will be unable to read; he or she will have no clear vision, because all objects will appear white, gray, or black; the diver will have to look off-center to see rather than looking directly at an object. Moreover, in order to see at all, the diver must dark-adapt.

In air, an individual can gradually adapt to nighttime light levels during twilight and probably not notice the change in vision; however, a diver may go directly from bright sunlight on the boat into a dark underwater world and be completely blind. To function effectively, the diver's eyes must adjust to the dim illumination for as long as 30 minutes if he or she has been in bright light. Some adaptation will take place while the diver descends, but the rate of descent cannot be slow enough to make this a practical solution, and other techniques are required. This is especially important during dives in which the bottom time is short and visual observation important.

The most effective way to become dark-adapted is to remain in the dark for 15 to 30 minutes before the dive. If this is impossible, red goggles are recommended.

Table 2-3
Colors That Give Best Visibility
Against a Water Background

Water Condition	Natural Illumination	Incandescent Illumination	Mercury Light
Murky, turbid water of low visibility (rivers, harbors, etc.)	Fluorescent yellow, orange, and red	Yellow, orange, red, white (no advantage in fluorescent paint)	Fluorescent yellow-green and yellow-orange
	Regular yellow, orange, and white		Regular yellow, white
Moderately turbid water (sounds, bays, coastal water)	Any fluorescence in the yellows, oranges, or reds	Any fluorescence in the yellows, oranges, or reds	Fluorescent yellow-green or yellow-orange
	Regular paint of yellow, orange, white	Regular paint of yellow, orange, white	Regular yellow, white
Clear water (Southern water, deep water offshore, etc.)	Fluorescent paint	Fluorescent paint	Fluorescent paint

Note: With any type of illumination, fluorescent paints are superior.
a. With long viewing distances, fluorescent green and yellow-green are excellent.
b. With short viewing distances, fluorescent orange is also excellent.

Adapted from NOAA (1979)

The night vision system of the eye is relatively insensitive to red light; consequently, if a red filter is worn over the face plate before diving, the eyes will partially adapt and at the same time there will be enough light for the day vision system to continue to function. The red filter should be worn for 10 to 15 minutes and *must* be removed before the dive. Because high visual sensitivity is reached sooner when this procedure is used, visual underwater tasks can be performed at the beginning of the dive instead of 20 to 30 minutes later. If it is necessary to return to the surface even momentarily, the red filter should be put on again, because exposure to bright light quickly destroys the dark-adapted state of the eye.

2.9 ACOUSTICS

Sound is a periodic motion of pressure change transmitted through a gas (air), a liquid (water), or a solid (rock). Since liquid is a denser medium than gas, more energy is required to disturb its equilibrium. Once this disturbance takes place, sound travels farther and faster in the denser medium. Several aspects of underwater sound are of interest to the working diver.

During diving operations, there may be two or more distinct contiguous layers of water at different temperatures; these layers are known as thermoclines. The colder a layer of water, the greater its density; as the difference in density between layers increases, less sound energy is transmitted between them. This means that a sound heard 164 feet (50 meters) from its source within one layer may be inaudible a few meters from its source if the diver is in another layer.

In shallow water or in enclosed spaces, reflections and reverberations from the air/water and object/water interfaces will produce anomalies in the sound field, i.e., echoes, dead spots, and sound nodes. When a diver is swimming in shallow water, among coral heads, or in enclosed spaces, periodic losses in acoustic communication signals and disruption of signals from acoustic navigation beacons are to be expected. The problem becomes more pronounced as the frequency of the signal increases.

The use of open-circuit scuba affects sound reception by producing high noise levels at the diver's head and by creating a screen of bubbles that reduces the effective sound pressure level (SPL). If several divers are working in the same area, the noise and bubbles will affect communication signals more for some divers than for others, depending on the position of the divers in relation to the communicator and to each other.

A neoprene wet suit is an effective barrier to sound at frequencies above 1000 Hz, and it becomes more of a barrier as frequency increases. This problem can be overcome by exposing a small area of the head either by cutting holes 0.79 to 1.18 in. (2 to 3 cm) at the temples or above the ears of the hood.

The human ear is an extremely sensitive pressure detector in air, but it is less efficient in water. A sound must therefore be more intense in water (+20 dB to 60 dB, SPL) to be heard. Hearing under water is very similar to trying to hear with a conductive hearing loss under surface conditions: a smaller shift in pressure is required to hear sounds at the extreme high and low frequencies, because the ear is not as sensitive at these frequencies. The SPL necessary for effective communication and navigation is a function of the maximum distance between the diver and the source (-3 dB SPL for every doubling of the distance between the source and the measurement point), the frequency of the signal, the ambient noise level and frequency spectrum, type of head covering, experience with diver-communication equipment, and the diver's stress level.

The use of sound as a navigation aid or as a means of locating an object in the environment depends primarily on the difference in the time of arrival of the sound at the two ears as a function of the azimuth of the source. Recent experiments have shown that auditory localization cues are sufficient to allow relatively precise sound localization under water. Moreover, it has been demonstrated that under controlled conditions divers are able to localize and navigate to sound beacons (Hollien and Hicks 1983). This research and practical experience have shown that not every diver is able to localize and navigate to sound beacons under all conditions. In general, successful sound localization and navigation depend on clearly audible pulsed signals of short duration that have frequency components below 1500 Hz and above 35,000 Hz and are pulsed with a fast rise/decay time.

Sound is transmitted through water as a series of pressure waves. High intensity sound is transmitted by correspondingly high intensity pressure waves. A diver may be affected by a high intensity pressure wave that is transmitted from the surrounding water to the open spaces within the body (ears, sinuses, lungs). The pressure wave may create increased pressure within these open spaces, which could result in injury.

The sources of high intensity sound or pressure waves include underwater explosions and, in some cases, sonar. Low intensity sonars such as depth finders and fish finders do not produce pressure waves of an intensity dangerous to a diver. However, some military anti-submarine sonar-equipped ships do pulse high intensity pressure waves dangerous to a diver. It is prudent to suspend diving operations if a high-powered sonar transponder is being operated in the area. When using a diver-held pinger system, it is advisable for the diver to wear the standard 1/4-inch (0.64-cm) neoprene hood for ear protection. Experiments have shown that such a hood offers adequate protection when the ultrasonic pulses are of 4-ms duration, are repeated once per second for acoustic source levels up to 100 watts, and are at head-to-source distances as short as 4 inches (10 cm).

SECTION 3
DIVING PHYSIOLOGY

DIVING PHYSIOLOGY 3

3.0 GENERAL

This section provides divers with basic information about how the body reacts to physiological stresses that are imposed by diving and how to compensate for these stresses and other physical limitations. Divers should become familiar with the terminology used in this chapter to understand and be able to describe any diving-related symptoms or physical problems they experience. Commonly used diving medical terms are defined in the glossary of this manual (Appendix E).

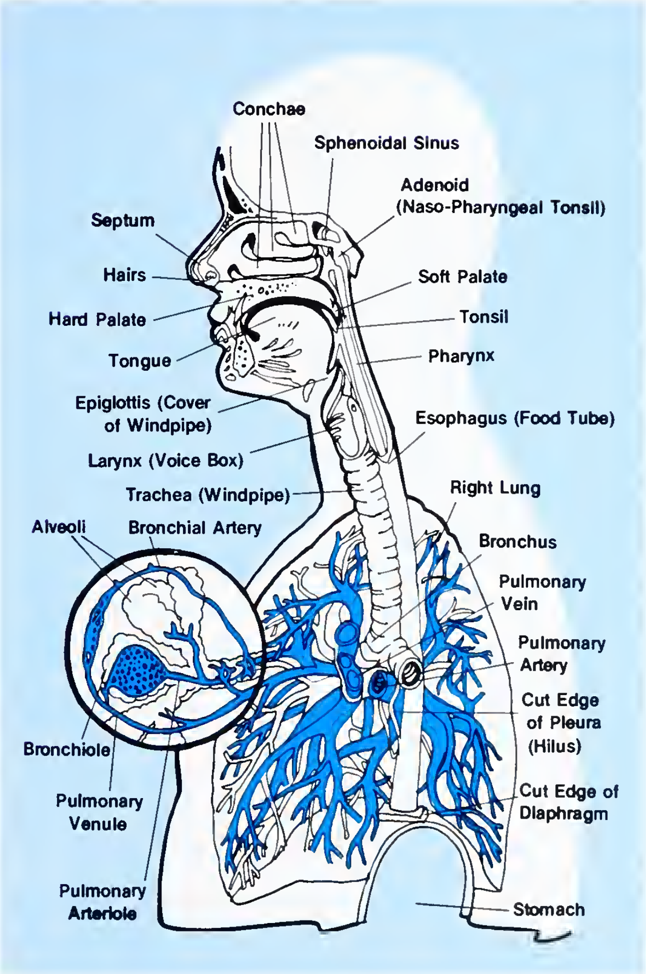
3.1 CIRCULATION AND RESPIRATION

The activity of each cell of the body involves several delicate reactions that can take place only under well-defined chemical and physiological conditions. The chief function of the circulatory system is to maintain conditions around the cells at the level that is optimal for their functioning. The regulation of cardiac output and the distribution of the blood are central to the physiology of circulation.

Respiration is the process by which gases, oxygen, and carbon dioxide are interchanged among the tissues and the atmosphere. During respiration, air enters the lungs via the nose or mouth and then traverses the pharynx, larynx, trachea, and bronchi. Air being exhaled follows this path in reverse. The bronchi enter the lungs and divide and re-divide into a branching network, ending in the terminal air sacs (alveoli), which are approximately one ten-thousandth of an inch (0.003 millimeter) in diameter. The alveoli are surrounded by a thin membrane, and the interchange of gases takes place across this membrane, where the blood in the tiny pulmonary capillaries takes up oxygen and gives off carbon dioxide. This process is shown schematically in Figure 3-1.

Before discussing diving physiology, a basic understanding of circulation, respiration, and certain problems associated with the air-containing compartments of the body is necessary. These topics are discussed in the following paragraphs.

Figure 3-1
The Process of Respiration



Source: NOAA (1979)

3.1.1 Circulatory System

The heart is divided vertically into the right and left sides, each consisting of two communicating chambers, the auricles and ventricles. Blood is pumped by the right ventricle into the pulmonary artery, through the pulmonary capillaries, and back to the left side of the heart through the pulmonary veins. The left ventricle pumps the blood into the aorta, which distributes it to the body. This distribution is accomplished by a continual branching of arteries, which become smaller until they become capillaries. The capillaries have a thin wall through which gases and other substances are interchanged between the blood and the tissues. Blood from the capillaries flows into the venules, the veins, and, finally, is returned to the heart. In this way, carbon dioxide produced in the tissues is removed, transported to the lungs, and discharged. This process is shown schematically in Figure 3-2.

During exercise, there is an increase in the frequency and force of the heart beat as well as a constriction of the vessels of the skin, alimentary canal, and quiescent muscle. Peripheral resistance is increased and arterial pressure rises. Blood is expelled from the spleen, liver, skin, and other organs, which increases circulatory blood volume. The net result of this process is an increase in the rate of blood flow to the body organs having a high demand for oxygen—the brain, the heart, and any active muscles.

3.1.2 Mechanism of Respiration

The chest wall encloses a cavity, the volume of which is altered by the rhythmic contraction and relaxation of muscles. This thoracic cavity contains the lungs, which are connected with the outside environment through the bronchi, the trachea, and the upper respiratory passages and the heart and great vessels. When the volume of the thoracic cavity changes, a decrease or increase in pressure occurs within the internal chambers and passages of the lungs. This change causes air to flow into or out of the lungs through the respiratory passageways until the pressure everywhere in the lungs is equalized with the external pressure. Respiratory ventilation consists of rhythmic changes of this sort. Respiration is affected by the muscular action of the diaphragm and chest wall and is under the control of the nervous system, which itself is responding to changes in blood oxygen and carbon dioxide levels. The normal respiratory rate at rest varies from about 12 to 16 breaths a minute. During and after heavy exertion, this rate increases severalfold.

In the chest wall's normal resting position, that is, at the end of natural expiration, the lungs contain about 2.5 liters of air. Even when one voluntarily expels all the air possible, there still remain about 1.5 liters of residual air. The volume of air that is inspired and expired during rest is referred to as tidal air and averages about 0.5 liter per cycle. The additional volume from the resting expiratory position of 2.5 liters that can be taken in during a maximal inspiration varies greatly from individual to individual, ranging from about 2 to 6 liters. The total breathable volume of air, called the **vital capacity**, depends on the size, development, age, and physical condition of the individual. Vital capacity is defined as the maximal volume that can be expired after maximal inspiration. A reduction in vital capacity limits the ability of a person to respond adequately to a demand for increased ventilation during exercise. Because diving often requires strenuous exercise, cardiovascular or respiratory disorders may seriously limit or prevent an individual from actively participating in this activity.

3.1.2.1 Pulmonary Ventilation

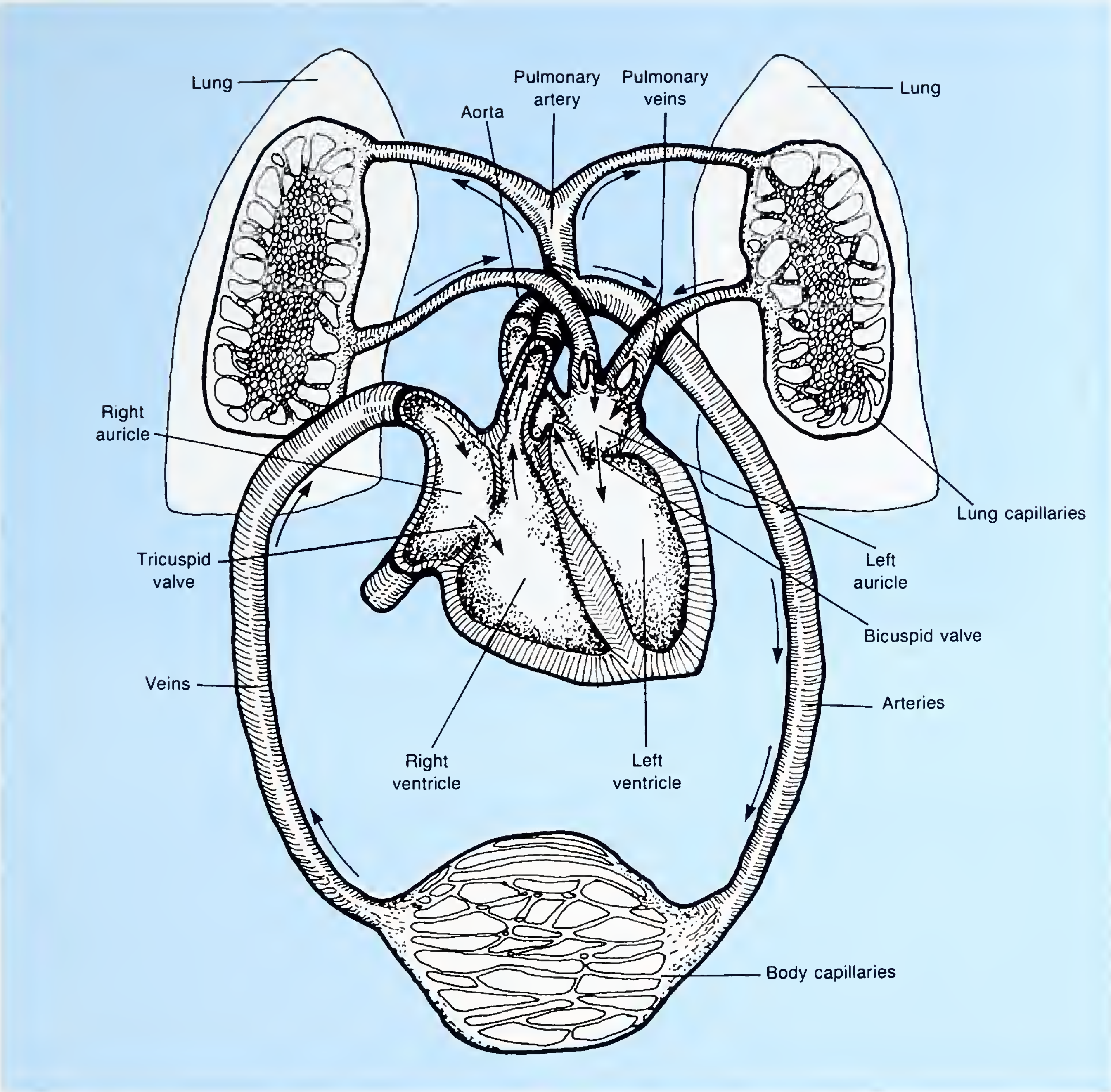
Air drawn into the lungs is distributed through smaller air passages until it reaches the honeycomb-like alveoli or air sacs through which the exchange of respiratory gases takes place (see Figure 3-1). The rates at which oxygen is supplied and carbon dioxide removed from the lungs depend on several factors: (1) the composition and volume of the air supplied through the respiratory passages; (2) the partial pressures of respiratory gases in the blood; and (3) the duration for which a given volume of blood is exposed to alveolar air. In a normal person in good physical condition, other factors influencing respiratory exchange are not likely to be significant.

At rest, about 0.3 liter of oxygen is used by the tissues per minute. During exercise, an exchange of about 3.5 liters or more of oxygen per minute may take place. This flexibility is accomplished by increased frequency of breathing, increased heart action propelling blood through the pulmonary capillaries, and increased differences in the partial pressures of oxygen and carbon dioxide during exercise. Figure 3-3 depicts oxygen consumption as a function of work rate. Normally, despite wide differences in the rates of gaseous exchange in the resting and heavy exercise conditions, the blood leaving the lungs is almost completely saturated with oxygen and in equilibrium with the alveolar carbon dioxide pressure.

3.1.2.2 Blood Transport of Oxygen and Carbon Dioxide

Blood can take up a much greater quantity of oxygen and carbon dioxide than can be carried in simple solution. Hemoglobin, which is the principal constituent in red blood cells and gives the red color to blood, has a chemical property of combining with oxygen and with carbon dioxide and carbon monoxide. The normal hemoglobin content of the blood increases the blood's oxygen-carrying capacity by about 50 times. The reaction between oxygen and hemoglobin is governed primarily by the partial pressure of oxygen. At sea level, where there is normally an inspired oxygen partial pressure of 150 millimeters of mercury, the alveolar hemoglobin becomes about 98 percent saturated in terms of its

Figure 3-2
The Circulatory System

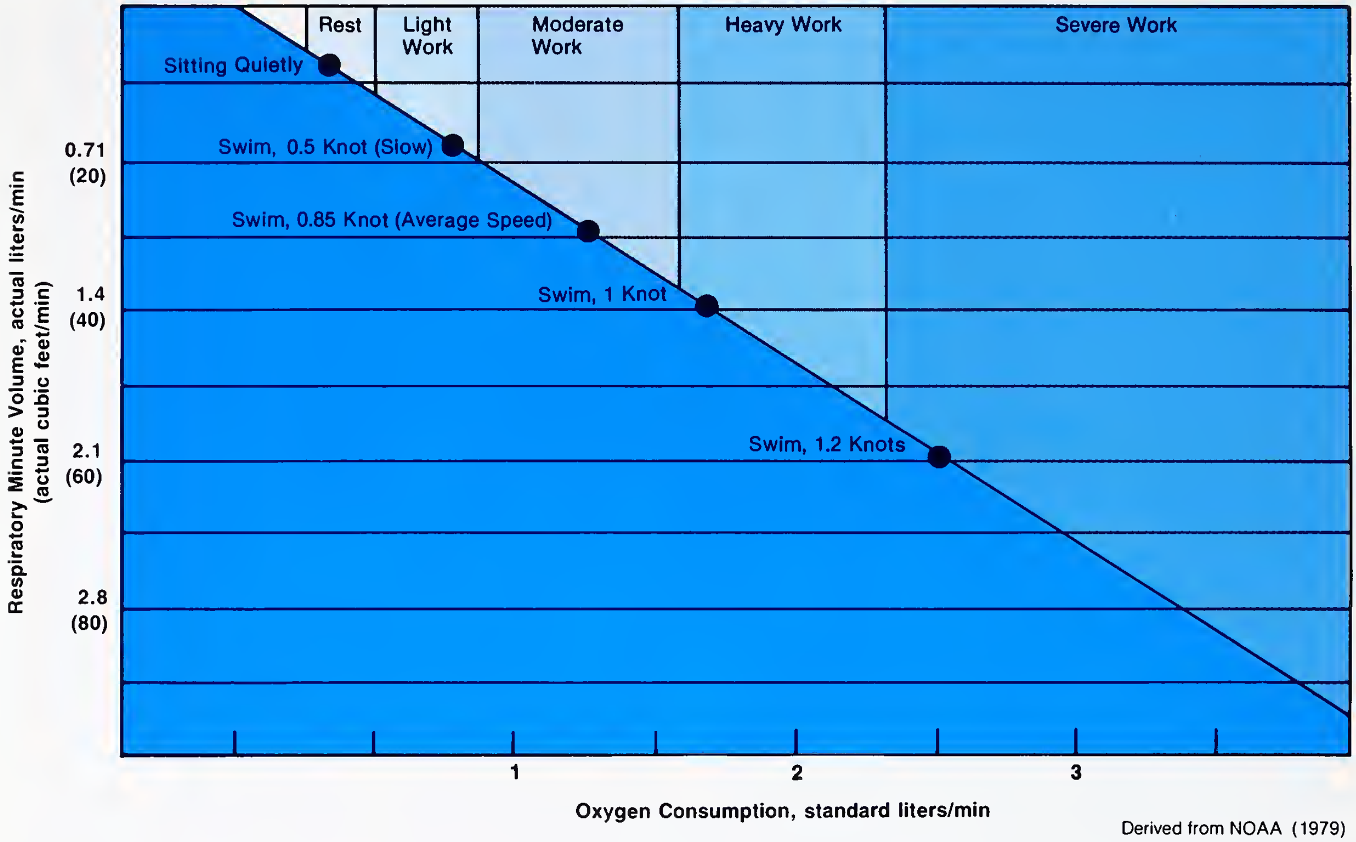


Source: Shilling, Werts, and Schandelmeier (1976)

capacity to form oxy-hemoglobin. In the tissues, where the partial pressure of oxygen is normally about 20 millimeters of mercury, between one-third and one-half of this oxygen is given up by hemoglobin and made available to the tissues. It is apparent that the blood of persons lacking a sufficiency of hemoglobin, i.e., anemic persons, will be deficient in its capacity to carry oxygen. As a consequence, anemic people are generally less fit for diving than people who are not anemic.

The blood contains a small amount of carbon dioxide in simple solution, but a greater amount is found in chemical combinations such as carbonic acid, bicarbonate, or bound to hemoglobin. All the forms of carbon dioxide tend toward chemical equilibrium with each other. The taking up of oxygen by the hemoglobin in the lung capillaries favors the unloading of carbon dioxide at the same time that the absorption of carbon dioxide into the blood in the tissues favors the release of oxygen.

Figure 3-3
Oxygen Consumption and Respiratory Minute Volume as a Function of Work Rate



Derived from NOAA (1979)

3.1.2.3 Gas Exchange in the Tissues

The exchange of oxygen and carbon dioxide between the blood and body cells occurs in opposite directions. Oxygen, which is continuously used in the tissues, exists there at a lower partial pressure than in the blood. Carbon dioxide is produced inside the tissue cells, which increases its concentration relative to that of the blood reaching the tissues. Therefore, blood supplied by the arteries gives up oxygen and receives carbon dioxide during its transit through the tissue capillaries. The rate of exchange of these respiratory gases and the total amount of gas movement depend on their respective partial pressure differences, since the exposure time of blood in the tissue capillaries is adequate for nearly complete equilibration to be achieved. When tissues are more active, the need for oxygen is greater. The increased oxygen is supplied not from an increase in the oxygen content of the arterial blood but by the larger volume of blood that flows through the tissues and by a more complete release of oxygen from a given volume of the blood. There can be as much as a ninefold increase in the rate at which oxygen is supplied to active tissues.

3.1.2.4 Tissue Need for Oxygen

All living tissues need oxygen, but tissues that are especially active during exertion, such as skeletal muscle, need greater amounts of oxygen. The brain, however, is made up of tissue that has an extraordinarily high and nearly steady requirement for oxygen. Although the nervous system represents only about 2 percent of the body weight, it requires about 20 percent of the total circulation and 20 percent of the total oxygen used by the body per minute at work or at rest. If circulation is completely cut off, consciousness may be lost in about one-quarter of a minute and irreparable damage to the higher centers of the brain may occur within 3 to 5 minutes (see Section 3.1.3.1).

3.1.2.5 Summary of Respiration Process

The process of respiration includes six important phases:

(1) Breathing or ventilation of the lungs;
(2) Exchange of gases between blood and air in the lungs;
(3) The transport of gases carried by the blood;

(4) Exchange of gases between blood and body tissues;
(5) Exchange of gases between the tissue fluids and cells; and
(6) Use and production of gases by the cells.

Each phase of this process is important to the life of the cells, and the process must be maintained constantly by the respiratory and circulatory systems.

3.1.3 Respiratory Problems

Although most physiological problems associated with diving are related to the breathing of gases at the high pressures encountered under water, respiratory problems may occur at the surface as well. These problems are generally related to the inadequate transport of oxygen to the cells and to the inadequate removal of carbon dioxide. Some of the common respiratory problems are **hypoxia, hypercapnia,** and **carbon monoxide poisoning.** Each of these is discussed in the following paragraphs.

3.1.3.1 Hypoxia

The term **hypoxia**, or oxygen shortage, is used to mean any situation in which tissue cells fail to receive or are unable to obtain enough oxygen to maintain their normal functioning. Hypoxia can occur as a result of interference with any phase of the oxygen transport process.

Hypoxia stops the normal function of cells. Brain tissue cells are the most susceptible of all body cells to hypoxia; unconsciousness and death can occur before the effects of hypoxia are apparent on other cells. Hypoxia may cause sudden unconsciousness or, if onset is gradual, may decrease the ability to think clearly, orient oneself, or to perform certain tasks. Confusion and difficulty in standing, walking, and maintaining coordination often follow. Victims of hypoxia may be unaware of impending trouble even though they become drowsy and weak. A particular danger of hypoxia is that as it progresses, it causes a false sense of well-being that may prevent the diver from taking corrective action soon enough. If hypoxia is severe and sudden, unconsciousness develops almost at once; unconsciousness usually occurs when the inspired partial pressure of oxygen falls to 0.10 atmosphere, i.e., equivalent to the oxygen pressure prevailing when a person breathes a 10 percent oxygen mixture at atmospheric pressure. Below this level, permanent brain damage and death occur quickly (US Navy 1985).

If a diver suffering from severe hypoxia is not rescued quickly, the interference with brain function will cause failure of breathing control. If given fresh air promptly before breathing stops, the diver usually will regain consciousness shortly and recover completely. If breathing has stopped but heart action continues, cardiopulmonary resuscitation may enable oxygen to reach the brain and revive the breathing control center so that spontaneous breathing will resume. It is difficult to know when the heart action has stopped completely, so efforts at resuscitation must be continued until medical attendants pronounce a victim dead.

WARNING

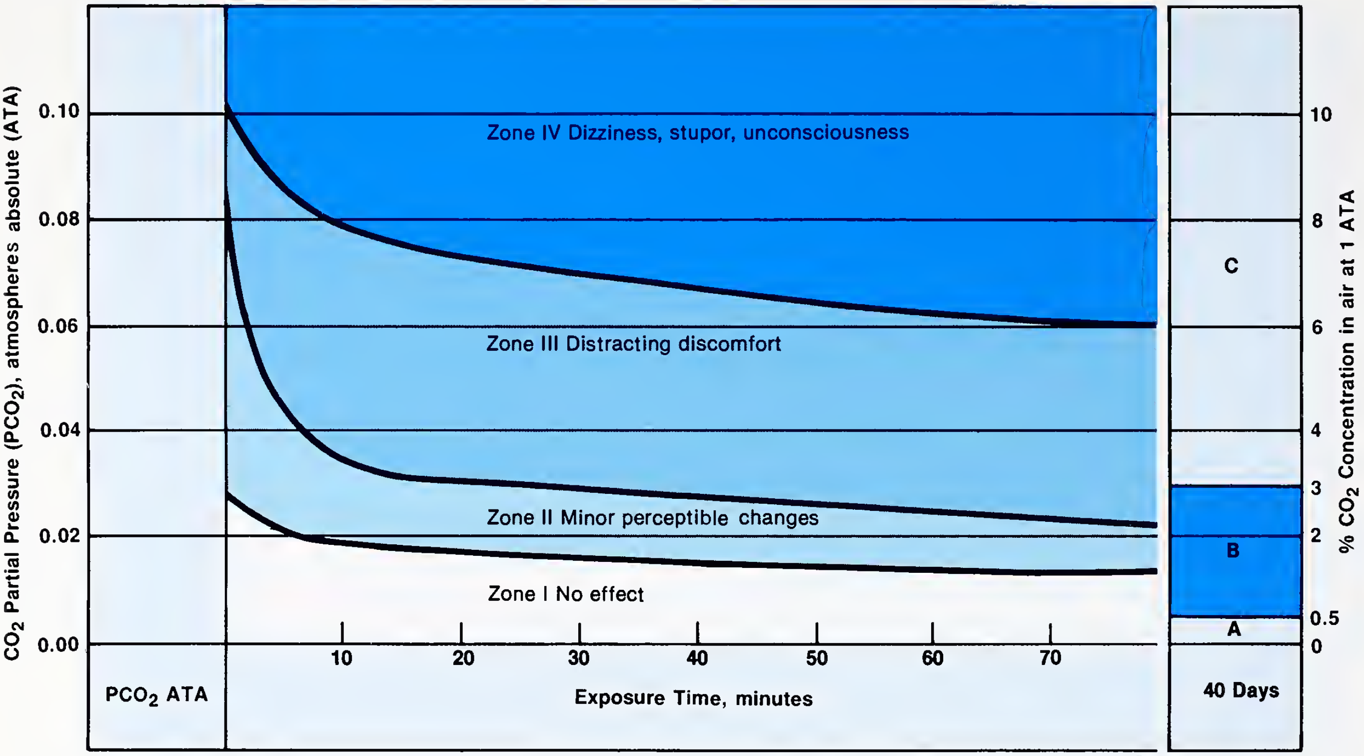
There Is No Natural Warning That Tells a Diver of the Onset of Hypoxia

3.1.3.2 Carbon Dioxide Excess (Hypercapnia)

An excess of carbon dioxide in the tissues can occur if the process of carbon dioxide transport and elimination is interrupted or modified. In diving, **carbon dioxide excess** occurs either because there is too much carbon dioxide in the diver's breathing medium or because the carbon dioxide that is produced is not eliminated properly. The diver's own metabolic processes are generally the source of any excess carbon dioxide. The proper carbon dioxide level is maintained in the body by respiration rapid enough to exhale the carbon dioxide produced and delivered to the lungs. For breathing to be effective, the air inhaled must contain a minimum of carbon dioxide. Inadequate helmet or mask ventilation, too large a dead space in mouthpiece or tubing, or failure of the carbon dioxide absorption system of closed- or semi-closed-circuit breathing systems may produce an excess of carbon dioxide in the gas breathed.

All tissues are affected by an excess of carbon dioxide, but the brain is the most susceptible organ to hypercapnia. Figure 3-4 shows the physiological effects of different concentrations of carbon dioxide for various exposure periods. At the concentrations and durations represented by Zone I, no perceptible physiological effects have been observed. In Zone II, small threshold hearing losses have been found and there is a perceptible doubling in the depth of respiration. In Zone III, the zone of distracting discomfort, the symptoms are mental depression, headache, dizziness, nausea, 'air hunger,' and a decrease in visual discrimination. Zone IV represents marked physical distress associated with dizziness and stupor, which is accompanied by an inability to take steps for self-preservation. The final stage of the Zone IV state is unconsciousness. Above a CO_2 partial pressure (PCO_2) of 0.15 ATA, muscle spasms, rigidity, and death can occur. If an excess of

Figure 3-4
Relation of Physiological Effects to Carbon Dioxide Concentration and Exposure Period



Derived from NOAA (1979)

carbon dioxide causes a diver to lose consciousness, he or she can be revived quickly if the lungs are ventilated with fresh air. The aftereffects of hypercapnia include headache, nausea, dizziness, and sore chest muscles.

The bar graph at the right of Figure 3-4 extends the period of exposure shown to 40 days. It illustrates that, for exposures of 40 days, concentrations of carbon dioxide in air of less than 0.5 percent (0.005 ATA partial pressure) (Zone A) cause no biochemical or other effects; concentrations between 0.5 and 3.0 percent (0.005-0.03 ATA partial pressure) (Zone B) cause adaptive biochemical changes, which may be considered a mild physiological strain; and concentrations above 3.0 percent (0.03 ATA partial pressure) (Zone C) cause pathological changes in basic physiological functions. For normal diving operations, ventilation rates should be maintained so that carbon dioxide partial pressures are maintained in Zones I and II for short-term exposures and in Zones A and B for long-term exposures.

Increased carbon dioxide in the breathing-mixture stimulates the respiratory center to increase the breathing rate. Carbon dioxide at a partial pressure of 0.02 atmosphere generally increases breathing noticeably.

When the carbon dioxide level reaches a partial pressure of 0.05 atmosphere, an uncomfortable sensation of shortness of breath occurs. There are large differences in individual responses to increases in carbon dioxide. The amount of work, the depth, and the breathing medium are factors that will also alter the effect of an increase in carbon dioxide on breathing. Deliberately reducing one's breathing rate will cause a carbon dioxide buildup; maintaining an adequate ventilation rate is necessary to remove carbon dioxide from the lungs effectively. Other conditions that increase the likelihood of carbon dioxide poisoning include severe exertion, high partial pressures of oxygen, high gas density, and the use of breathing apparatus that has excessive dead space or high breathing resistance.

WARNING

Skip-Breathing Is Not a Safe Procedure Because Carbon Dioxide Buildup Can Occur With Little or No Warning

3.1.3.3 Carbon Monoxide Poisoning

Inspired carbon monoxide (CO) combines with hemoglobin in the red blood cells, rendering them incapable of carrying oxygen to the tissues. When carbon monoxide is bound to hemoglobin, a person experiences tissue hypoxia (oxygen deficiency in the tissues) even though the air being breathed has sufficient oxygen. This condition is known as **CO poisoning**. Hemoglobin combines with carbon monoxide about 210 times more readily than with oxygen, so very small concentrations of carbon monoxide can be dangerous to life (US Navy 1985). The hemoglobin-carbon monoxide combination is red in color and may cause an unnatural redness of the lips and skin. However, since this redness may not occur, carbon monoxide poisoning cannot be ruled out simply because a person has normal coloring. In addition to its effects on hemoglobin, carbon monoxide combines with the final respiratory enzyme (cytochrome oxidase a_3) in the tissues, causing hypoxia at the tissue level as well. Because carbon monoxide poisoning interferes with the delivery of oxygen to the tissues, the symptoms are identical to those of other types of hypoxia. If the concentration of carbon monoxide is high enough to cause rapid poisoning without the diver's awareness, he or she may lose consciousness suddenly. If the carbon monoxide poisoning is more gradual in onset, pounding headache, nausea, and vomiting may occur.

A diver's breathing gas can be contaminated by carbon monoxide if the compressor supplying the breathing gas draws from an area where the air is contaminated by the exhaust from a gasoline or diesel engine or if vapor from the oil used to lubricate the compressor gets into the air supply. It is essential that the air intakes on compressors be protected to avoid this source of carbon monoxide contamination and that oil with an appropriate flash point is used in any oil-lubricated compressor that supplies divers' breathing air (see Section 4.2.2).

When a diver loses consciousness, it is routine to administer recompression treatment because of fear that either decompression sickness or an arterial gas embolism has caused the loss of consciousness. Occasionally, carbon monoxide poisoning is the cause of unconsciousness, and recompression treatment, using either USN Treatment Table 5 (Oxygen Treatment of Type I Decompression Sickness; US Navy 1985) or a hyperbaric oxygen treatment table designed specifically to treat carbon monoxide poisoning, is the treatment of choice in these cases as well. Carbon monoxide poisoning victims who resume breathing and regain consciousness quickly have a good chance of complete recovery.

3.1.3.4 Smoking

Smoking directly affects the oxygen-carrying capability of the red blood cells. The smoke of a typical American cigarette contains about 4 percent carbon monoxide (40,000 ppm). The average carbon monoxide concentration inhaled during the smoking of one cigarette is 400-500 ppm, which produces anywhere from 3.8 to 7.0 percent carboxyhemoglobin (HbCO) in the blood; in non-smokers, the HbCO level is generally 0.5 percent. The percentage of HbCO blood levels after continuous exposure to carbon monoxide for 12 hours or after reaching equilibrium are summarized in the table below.

Continuous Exposure Level of CO, ppm	HbCO in Blood %
50	8.4
40	6.7
30	5.0
20	3.3
10	1.7
—	0.5 (non-smoker)

Source: NOAA (1979)

Table 3-1 shows the relationship between smoking and HbCO blood levels. This table shows that the HbCO level in the blood of divers who smoke is higher than it would be if the divers had been exposed to 20 ppm carbon monoxide for 12 hours (equivalent to the maximum carbon monoxide level allowed in divers' breathing air by the U.S. Navy (see Table 15-6)). Considering that it takes a heavy smoker approximately 8 hours to eliminate 75 percent of the carbon monoxide inhaled, it is clear that the HbCO level (0.95 percent) even for a light smoker diving 8 hours after the last cigarette is almost twice that of a non-smoker (0.50 percent). The carboxyhemoglobin blood level of a passive smoker (i.e., a person who does not smoke but who is exposed to the smoke of others) can rise to 5 percent after exposure to a smoke-filled environment (Surgeon General 1986).

The dose of carbon monoxide a smoker receives from smoking is toxic; it causes changes in neurologic reflexes, psychomotor test results, sensory discrimination, and electrocardiograms, as well as fatigue, headache, irritability, dizziness, and disturbed sleep. Other short-term effects of smoking may also adversely affect the diver. For example, in addition to accelerating the atherosclerotic changes in blood vessels, cigarette smoke also raises blood pressure and increases heart rate. Smokers have trouble eliminating respiratory tract secretions, and the accumulation of these secretions can make equalizing pressure in the ears and sinuses difficult (Shilling, Carlston, and Mathias 1984). The irritants in inhaled tobacco smoke can cause an increase

Table 3-1
Carboxyhemoglobin as a
Function of Smoking

Smoking Habits	Median HbCO Level, %	Expired CO, ppm
Light smoker (less than ½ pack/day)	3.8	17.1
Moderate smoker (more than ½ pack/day and less than 2 packs/day)	5.9	27.5
Heavy smoker (2 packs or more/day)	6.9	32.4

Source: NOAA (1979)

in bronchial mucus and a chronic inflammatory change in the bronchial lining. Over a prolonged period, these conditions may result in structural weakness of the lung, such as emphysematous bullae, alveoli enlarged with air, or obstructive lung disease. Lung cysts can enlarge because of gas trapped by bronchial obstruction and may then rupture. The resulting tears can open into pulmonary veins, permitting gas embolism. Furthermore, nicotine and carbon monoxide increase the 'stickiness' of blood platelets, causing a clumping that can interfere with the flow of blood in the small vessels; this condition may increase a person's susceptibility to decompression sickness. In a study of 93 Navy divers, cigarette smoking was found to be associated with lung function decrement and to have an important and adverse effect on divers' health (Dembert et al. 1984). Other Navy research reported by Dembert and co-authors suggests that there is an association between smoking and the risk of decompression sickness.

The deleterious effects of smoking on the cardiorespiratory system clearly indicate that divers should not smoke. If divers are not able to stop smoking altogether, they should at least avoid smoking for several hours before diving.

3.1.3.5 Excessive Resistance to Breathing

Any breathing apparatus used by a diver under water will increase the work-of-breathing (i.e., the amount of work involved in breathing) to some extent. If the **breathing resistance** of the apparatus is high, it will be difficult to breathe adequately even during ordinary exertion and breathing will become impossible during hard work. Resistance to the flow of breathing gas is caused by demand regulators, valves, hoses, and other appurtenances of a life-support system. Well-designed equipment minimizes the amount of resistance to the flow of breathing gas (see Section 5.1.1.1).

The characteristics of the breathing gases flowing through tubes of various sizes and configurations influence the amount of breathing resistance encountered by a diver using the equipment. Gases moving through tubes of optimal design will flow 'in line' or in *laminar* flow until restrictions in or the dimensions of the tube cause the air molecules to begin moving in a disordered fashion (*turbulent* flow). The increase in the effort required to move gas that is in turbulent rather than laminar flow is significant: the resistance increases in relation to the square of the increased flow rate; that is, doubling the flow rate causes a fourfold increase in resistance (see Section 2.6). This may be a problem with small-bore snorkels, small-diameter exhaust valves, or inadequate breathing tubes and mouthpieces. Thus, snorkels should have diameters approximately 3/4 inch (1.9 centimeters) with no unnecessary bends, corrugations, or obstructions, and exhaust valves should be large enough to keep the exhalation resistance as low as possible (see Sections 5.1.1.4 and 5.6.1).

The position of the demand valve or breathing bag in relation to the internal pressure in the lungs is critical in closed-circuit scuba to avoid unbalanced hydrostatic pressure causing an increase in breathing resistance (Figure 3-5). As the work-of-breathing increases, the body reaches a point where it will accept increased carbon dioxide rather than perform the respiratory work required to maintain a normal carbon dioxide level in the tissues (US Navy 1985).

3.1.3.6 Excessive Dead Space

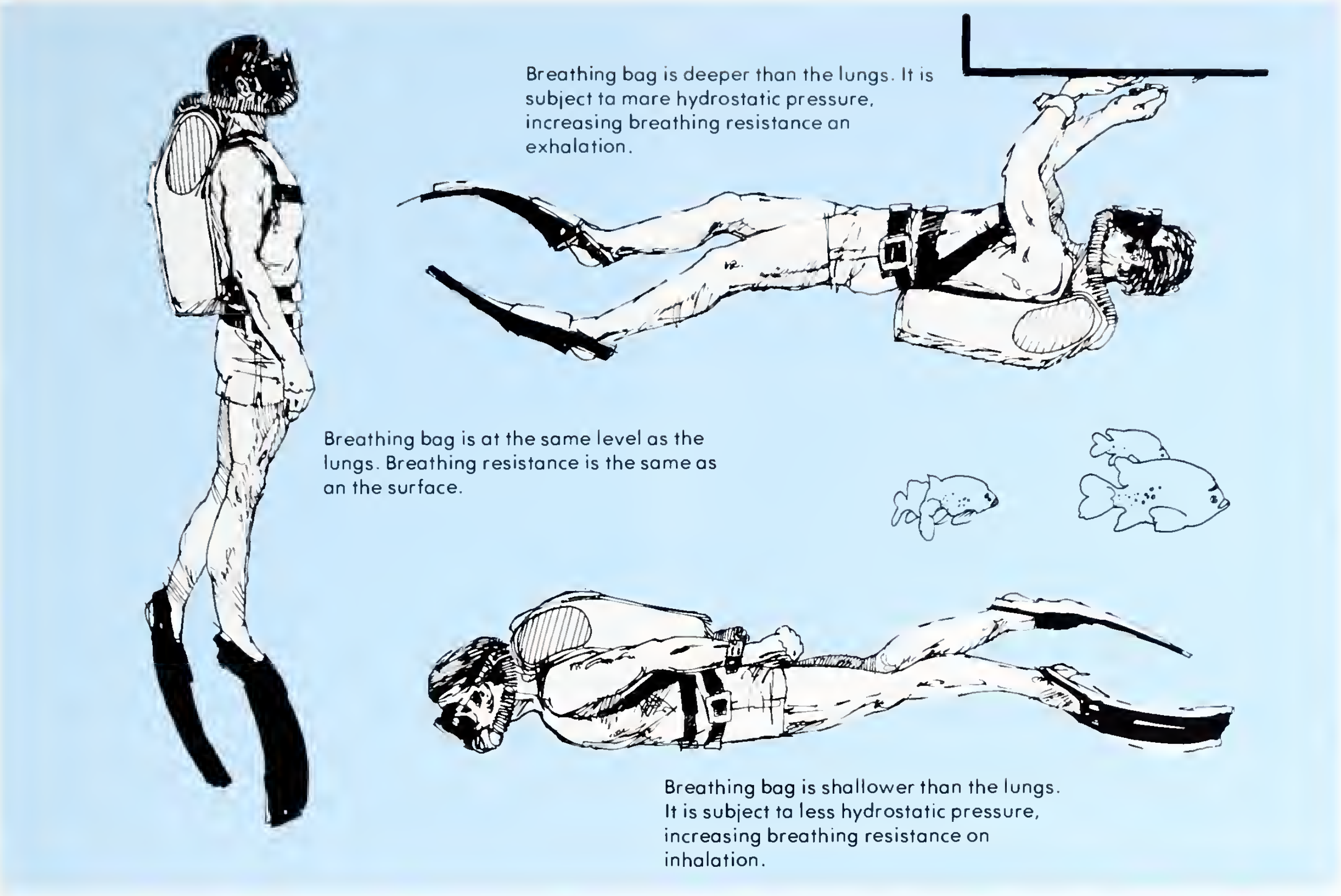
Dead space in a diving system is that space in which residual exhaled air remains. A diver exhaling into a snorkel, mouthpiece, or full-face mask may return some of this exhaled gas to the lungs; the amount returned depends on the dead space volume within the system. A well-designed system has minimum dead space. A casual examination of diving equipment will not reveal dead space volume; special equipment must be used to measure the extent of this ineffective volume by determining how much exhaled gas is actually rebreathed.

Full-face masks may add as much as 0.5 liter of dead space; this excess must be ventilated with each breath (US Navy 1985). Because of carbon dioxide buildup, the excess can seriously limit a diver's ability to do work. Free-flow helmets do not have this dead space problem. The use of oral-nasal masks inside full-face masks is effective in reducing the amount of dead space (see Section 5.2.1).

3.1.3.7 Hyperventilation and Breath-holding

The respiratory system utilizes both carbon dioxide (CO_2) and oxygen (O_2) tensions (partial pressures) in

Figure 3-5
Effects of Hydrostatic Pressure on Location of Breathing Bags Within a Closed-Circuit Scuba



Source: NOAA (1979)

the body to regulate the process of breathing. Rising CO_2 tension and falling O_2 tension are monitored by biological sensors in the body, which normally trigger the breathing response when the appropriate levels are reached. **Hyperventilation** (rapid, unusually deep breathing in excess of the necessary rate for the level of activity) interferes with the normal operation of the respiratory control mechanism. Hyperventilation lowers the CO_2 level in body tissues to levels below normal, a condition known as **hypocapnia**, which initially causes a feeling of lightheadedness and may cause weakness, faintness, headache, and blurring of vision over a longer period.

Voluntary hyperventilation, which occurs in distance underwater swimming or breath-holding competitions, is a dangerous practice. Hyperventilation lowers the carbon dioxide level without significantly increasing the oxygen level of the blood. When breath-holding after hyperventilation, oxygen levels can fall to levels resulting in unconsciousness before the CO_2 level is high enough to stimulate respiration. As a consequence, competitive underwater breath-holding events should be discouraged (Bove 1985).

Hyperventilation is often initiated by anxiety or physical stress or outright panic and may cause unconsciousness or muscle spasms. If either unconsciousness or spasm occurs in the water, the diver may drown. Some individuals are more susceptible to hyperventilation-induced hypocapnia than others; however, sufficiently prolonged hyperventilation induces unconsciousness or muscle spasms in most individuals.

Both scuba and surface-supplied divers should be aware of the problems associated with hyperventilation. Divers who notice that they are hyperventilating should take immediate steps to slow their breathing rate, notify their buddies, and, if feasible, ascend promptly. After reaching the surface, they should inflate their buoyancy compensators. Hyperventilating divers should not attempt to swim to a boat or the shore unaided because they may lose consciousness in the attempt. During surface-supplied diving, the tender should continuously monitor the diver's breathing for signs of hyperventilation. Divers starting to hyperventilate should be asked to stop work and rest. Once on the surface, holding the breath for short periods will aid in replenishing low CO_2 levels and may avert further complications.

3.2 EFFECTS OF PRESSURE

The effects of pressure on divers may be divided into two principal categories: (1) those that are direct and mechanical; and (2) those that come about because of changes in the partial pressure of inspired gases. With each 2-foot (0.61 meter) increase in the depth of seawater, the pressure increases by almost 1 psi. Each 33 feet (10 meters) of descent in seawater increases the pressure by an additional atmosphere (14.7 psi).

The lungs and respiratory passages contain air at all times. In addition to the major air channels, which include the nose, mouth, throat, larynx, and trachea, there are a number of side compartments issuing from the upper respiratory passages that are important in diving physiology. These include the eustachian tubes, the middle ear, and the paranasal sinuses. When the body is exposed to pressure changes, such as those that occur in diving, air contained in these cavities undergoes compression because the pressure of the air delivered by the breathing supply must be equilibrated with the pressure of the surrounding environment. The pressure of air breathed into and out of the lungs and respiratory passages thus also changes in accordance with changes in the surrounding hydrostatic pressure.

3.2.1 Direct Effects of Pressure During Descent

Humans can tolerate increased pressures if they are uniformly distributed throughout the body. However, when the outside pressure is different from that inside the body's air spaces, this difference in pressure may distort the shape of the involved tissues, causing injury. This is called **barotrauma**.

The pressure in such spaces as the sinuses and the middle ear must be equalized on descent, or pressure differences will develop across the walls of these spaces. Once the pressure at a given depth has been equalized, it must be allowed to decrease if the external pressure decreases, as occurs during ascent. The effects of pressure on various parts of the body are discussed in the following paragraphs.

3.2.1.1 The Ears

The air-containing external and middle ear gives humans a device that efficiently transforms airborne sound energy to the fluid-containing inner ear, where this energy is transduced into electrical signals. Proper functioning of this mechanism requires that both the external ear canal and the middle ear contain air and that differences in pressure be avoided between these structures and the ambient atmosphere or inner ear. The many changes in pressure regularly involved in diving make a pressure-sensitive middle ear a liability for a diver.

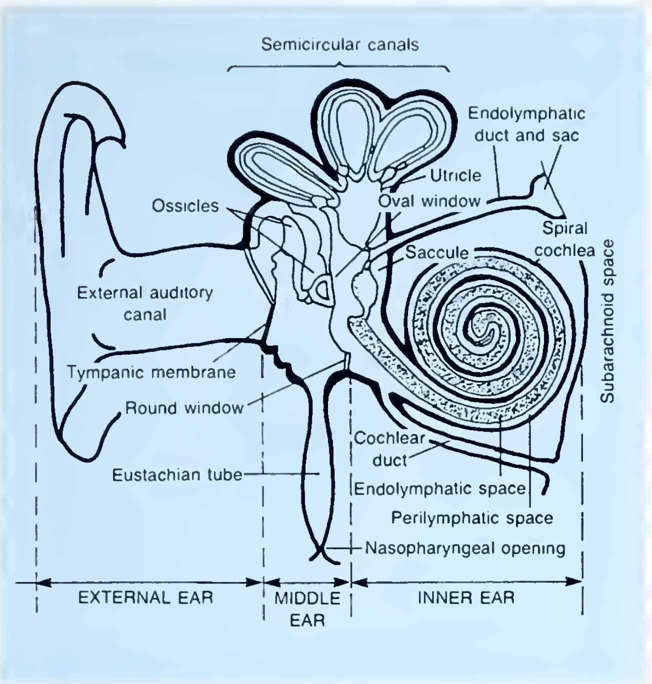
The effect of immersion on the human ear causes it to function differently under water than it does in air. Normally, sound is transmitted in air (which is easily compressed) in a high-amplitude (HA) low force mode. In liquid (which is difficult to compress), sound is transmitted in a low-amplitude (LA) high force mode. The human ear is designed to convert HA energy to LA energy (see Figure 3-6) by the mechanical processing of sound in the external and middle ear. In water, however, sound arrives at the ear in the LA mode, and the process of converting sound from LA to HA and back to LA is not efficient. As a result, the external/middle ear mechanisms are functionally bypassed under water and hearing is primarily achieved by bone (skull) conduction.

When divers experience extreme changes in ambient pressure, the ears may be injured unless the pressure between the air-containing cavity and the ambient atmosphere is equalized. **Barotitis media** (middle ear squeeze) resulting from inadequate pressure equalization between the middle ear and the ambient pressure is a fairly common problem among divers. Although occasionally disabling, it is usually reversible. Because more people are diving to deeper depths, there have been more serious and disabling problems involving the inner ear.

In terrestrial environments, balance and spatial orientation depend on input to the central nervous system from the visual, proprioceptive (sense of touch), and vestibular (sense of balance) systems. When people work beneath the sea, visual and proprioceptive cues are frequently distorted; thus, spatial orientation and balance become more dependent on information received from the vestibular system. Vestibular system dysfunction may occur in many phases of diving, and the subsequent vertigo, nausea (and, occasionally, vomiting) can be life threatening.

The middle ear space (Figure 3-6) connects with air cell systems in the skull bone containing the ear. With an intact eardrum membrane, the only communication between this system and the ambient atmosphere is through the eustachian tube. This tube is approximately 1.4 to 1.5 inches (3.5 to 3.8 cm) long in the adult and leads from the middle ear to the nasopharynx (or upper expanded portion of the throat) behind the nasal cavities. The nasopharyngeal opening normally is closed by positive middle ear pressure, or, when opened during swallowing, by muscular action on the surrounding cartilage.

Figure 3-6
Principal Parts
of the Ear



The air-containing external auditory canal, middle ear, and eustachian tube are noted. The fluid-filled inner ear is subdivided into the perilymphatic and endolymphatic spaces, which connect to the subarachnoid space by the cochlear duct and endolymphatic duct, respectively.

Source: Bennett and Elliott (1982), with the permission of Bailliere Tindall, Ltd.

The eustachian tube is lined by epithelium that is similar to the lining of the nose, sinuses, and nasopharynx. Abnormal nasal function can be caused by acute or chronic inflammatory diseases, allergy, chronic irritation from excessive smoking or prolonged use of nose drops, or chronic obstruction from internal or external nasal deformities or lesions. Nasal dysfunction may contribute to inadequate eustachian tube function, which may cause middle or inner ear barotrauma in divers (Sections 20.3.2 and 20.3.3).

Descent usually causes greater difficulty in equalizing the ear than ascent because the air passes from the middle ear more easily than into the middle ear from the nasopharynx. As descent or compression proceeds, middle ear pressure must be equalized constantly to prevent middle ear barotrauma with possible eardrum rupture or inner ear injury caused by rupture of the round window (see Figure 20-1). Successful methods of equalizing middle ear pressure are swallowing, yawning, or gently blowing against a closed mouth and nostrils. Forceful blowing (valsalva maneuver) should never be done because, if the middle ear pressure is already negative, forceful blowing, which causes an increase in cerebrospinal fluid and inner ear pressure, may rupture the round window. Injuries to the eardrum or inner ear may occur with as little as 3 pounds (1.3 kilograms) of pressure differential, and they may happen anywhere in the water column.

WARNING

Because Of The Danger Of Round Window Rupture, A Forceful Valsalva Maneuver Should Not Be Performed During Descent

The inner ear consists of a system of fluid-filled bony channels within the temporal bone (Figure 3-6). Membranous structures that are divided into two parts, the vestibular system containing the semi-circular canals and the auditory system, are located in these channels. These two systems are interconnected and have a common blood supply. Changes in cerebrospinal fluid pressure can be transmitted directly to the inner ear compartments, and therefore any maneuver such as straining, lifting, or trying to clear the ears against closed nasal passages can cause increased pressure in the ear's fluid-filled compartments. Marked pressure changes may cause ruptures between the inner and middle ear, leading to vertigo and hearing loss; this may happen even in shallow exposures.

In general, any individual who has difficulty with middle ear ventilation at the surface should not dive. Furthermore, individuals who have chronic nasal obstruction or a history of frequent upper respiratory infections, nasal allergies, mastoid or ear disease, or chronic sinus trouble should have a complete otolaryngological evaluation before diving. Also, individuals who have an upper respiratory infection of any kind should not dive until the infection has cleared.

Systemic and topical drugs may improve nasal function and sinus and middle ear ventilation. However, divers should use such agents cautiously because the rebound phenomenon that occurs after the drug, and especially topical nose drops, wears off may lead to greater nasal congestion and even greater equalization problems in the ears and sinuses. Prolonged use of topical nasal medications can cause chronic nasal irritation.

For safe diving, equalization problems must be avoided. For example, if a diver cannot clear his or her ears on the surface, he or she should not dive. Some steps to be followed during descent are:

- Descend feet first, preferably down the anchor line or a drop line. It is easier to equalize middle ear pressure in the upright position because drainage is more effective in this orientation.

- Clear the middle ear early, actively, and conscientiously during descent. Clearing by forceful blowing against a closed mouth and nose should be avoided, if possible.
- Stop the descent if ear blockage or fullness develops; the diver should ascend until these symptoms have cleared, even if return to the surface is required. Descent should not be continued until ear pain develops.

Inner-ear decompression sickness (also called **vestibular decompression sickness**) has occurred with no symptoms other than vertigo, ringing in the ears, or nausea (Farmer 1976). Vestibular decompression sickness is seen more commonly after deep helium-oxygen dives, particularly after a switch to air in the later stages of decompression, although it also has occurred in shallower air diving. Any diver with such symptoms during descent or compression should be considered as having inner ear barotrauma, including possible rupture of the oval and round windows, and should *not* be recompressed. Recompression would again subject the diver to unequal middle ear pressures. However, even if these precautions are heeded, hearing impairment can develop as a result of diving. For this reason, divers should have annual audiometric examinations.

NOTE

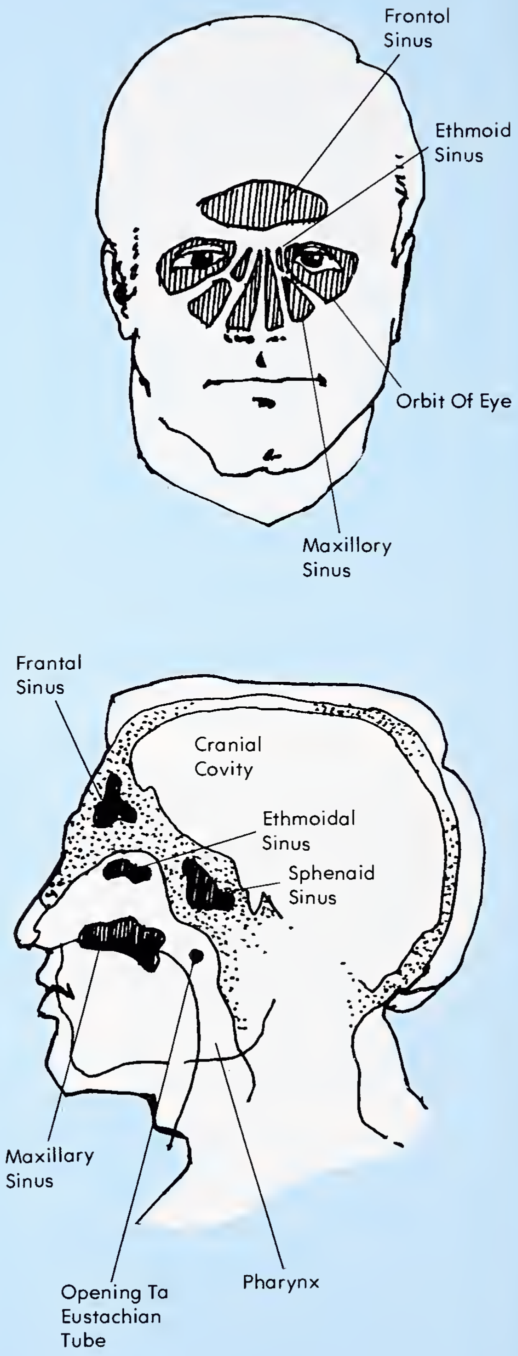
Any diver with ringing or roaring in the ears, loss of hearing, vertigo or dizziness, or nausea or vomiting during or shortly after decompression from a dive should be treated as having inner-ear decompression sickness.

3.2.1.2 The Sinuses

The sinus cavities are shown in Figure 3-7. Although **paranasal sinus barotrauma** occurs only rarely in divers, inflammation and congestion of the nose, nasal deformities, or masses can cause blockage of the sinus opening. This blockage leads to a series of changes within the cavities, consisting of absorption of pre-existing gas, vacuum formation, swelling, engorgement, inflammation of the sinus lining, or collection of fluid in the sinus cavity. When such blockage occurs during descent in diving or flying, the intra-sinus vacuum becomes greater and the resulting pathological changes are more severe; there may be actual hemorrhage into the sinus in some instances.

Paranasal sinus barotrauma also occurs during ascent; the mechanism of this trauma appears to be a blockage of a one-way valve of the sinus by inflamed mucosa, cysts, or polyps, which permits pressure equalization

Figure 3-7
Location of
Sinus Cavities



Source: NOAA (1979)

during descent but impairs it during ascent. The symptoms and management of paranasal sinus barotrauma are discussed in Sections 20.2.1 and 20.3.

3.2.1.3 The Lungs

As long as normal breathing takes place and the breathing supply is ample, the lungs and airways will equalize pressure without difficulty. If divers hold their breath during a pressure increase, no difficulty arises until the total volume of air in the lungs is compressed to less than the residual volume. Once the volume in the lungs becomes less than the residual volume, pulmonary congestion, swelling, and hemorrhage of the lung tissue occurs; this condition is called **thoracic squeeze**. Figure 3-8 graphically illustrates the effects of pressure on lung volume.

In breath-hold diving, no high-pressure air is available to the lungs. Pressure compresses the diver's chest and raises the diaphragm; pressure equalization results from the fall in lung volume, i.e., the effects of Boyle's Law ($P_1V_1 = P_2V_2$). Lung volume limits the extent of tolerable compression. Descending to 33 feet (10 meters) will reduce lung volume by one-half. Compression down to residual volume (the amount of air in the lungs after forceful expiration) can be tolerated; however, when chest compression exceeds this limit, tissue trauma occurs. Fluid from the capillaries and tissues then enters the alveoli and the air passageways and may cause gross hemorrhaging. Mild lung barotrauma causes only pain and a slight exudation, which is quickly reabsorbed, but in serious cases, the lungs may be damaged. This form of trauma generally responds well to conservative treatment consisting of general supportive care, prevention of infection, and intermittent positive-pressure inhalation therapy. Spraying with bronchodilators and aerosols and inducing gravitational drainage may prove beneficial if hemorrhage or bruising has been severe.

The use of a breathing apparatus that has a high inspiratory resistance may cause **pulmonary edema** (increased fluid in the tissues of the lungs). In an effort to maintain adequate lung ventilation during moderate activity, the small veins of the lungs may be damaged, fluid may seep through the membranes, and the alveoli may rupture. In addition, gas exchange can be hampered, which increases the risk of decompression sickness. Coughing and shortness of breath are symptoms of this condition, and x rays of the chest may show patchy pulmonary infiltration, which usually clears within 24 hours without specific therapy.

The lungs can be traumatized during the compression phase of a dive or treatment if an individual stops

Figure 3-8
Pressure Effects
on Lung Volume

At the surface
1 Atmosphere Absolute, 14.7 psi. The lungs are fully expanded with a full breath of air.

At 33 Feet
2 Atmospheres Absolute, 29.4 psi. Because of hydrostatic pressure, the same volume of air in the lungs is reduced to only ½ its surface volume.

Source: NOAA (1979)

breathing, either voluntarily by breath-holding or involuntarily because of windpipe or tracheal obstruction or convulsions.

3.2.1.4 The Teeth

Pain in the teeth (**barodontalgia**) can occur in diving and may be caused either by referred pain from the paranasal sinuses or by tooth squeeze. This latter condition, athough uncommon, is caused by a variety of dental conditions, such as new lesions or a lesion that has developed around the edge of an old filling (recurrent decay) (Rottman 1982). Tooth squeeze is not caused by air trapped in a filling. Other causes of tooth squeeze include recent extractions, gum infections that have formed periodontal pockets, large areas of decay where the pulp is infected, and recent fillings. Tooth squeeze can also occur if a person dives while undergoing root canal therapy. Part of the root canal procedure is to dry and seal the canal between treatments with a material that is designed to be adequate at a pressure of one atmosphere. Exposure to higher pressures, however, can produce small leaks in this material that are not able to release air fast enough during subsequent ascent. Like other squeezes, tooth squeeze usually subsides when the ambient pressure is reduced to one atmosphere. This mechanism also may be the explanation for tooth explosion (Rottman 1982). Gas that has accumulated slowly during a saturation dive can cause tooth explosion during or after decompression.

3.2.2 Direct Effects of Pressure During Ascent

During a pressure decrease (e.g., during ascent), the air in the body cavities expands. Normally, this air vents freely and there are no difficulties. If breathing is normal during ascent, the expanding lung air is exhaled freely. However, if the breath is held or there is a localized airway obstruction, the expanding air is retained, causing overinflation and overpressurization of the lungs. For example, the air in the lungs at a depth of 66 feet (20.1 meters) gradually expands to *three times* its volume during ascent to the surface (see Figure 3-8). The air volume can expand safely to the point of maximum inspiration, assuming there is no airway obstruction. If the pressure decreases further, **overexpansion** and **overpressurization of the lungs** may cause progressive distension of the alveoli. This overdistension may be general, which occurs with breath-holding or insufficient exhalation, or localized, which happens with partial or complete bronchial obstruction caused by the presence of bronchial lesions, mucus, or bronchospasm. For this reason, individuals with bronchial asthma should not do compressed gas diving of any type. Problems of lung overinflation can occur during ascent from depths as shallow as 4-6 feet (1.2-1.8 meters) if the breath is held. Several of the most commonly encountered physiological difficulties associated with pressure during ascent are described in the following paragraphs; each may be prevented by breathing normally during ascent, providing there is no localized airway obstruction. Figure 3-9 shows the possible consequences of overinflation of the lungs.

WARNING

A Diver Who Has Experienced Blowup (or an Overpressure Accident) Must Immediately Be Examined by a Physician

WARNING

Do Not Hold Breath While Ascending

3.2.2.1 Pneumothorax

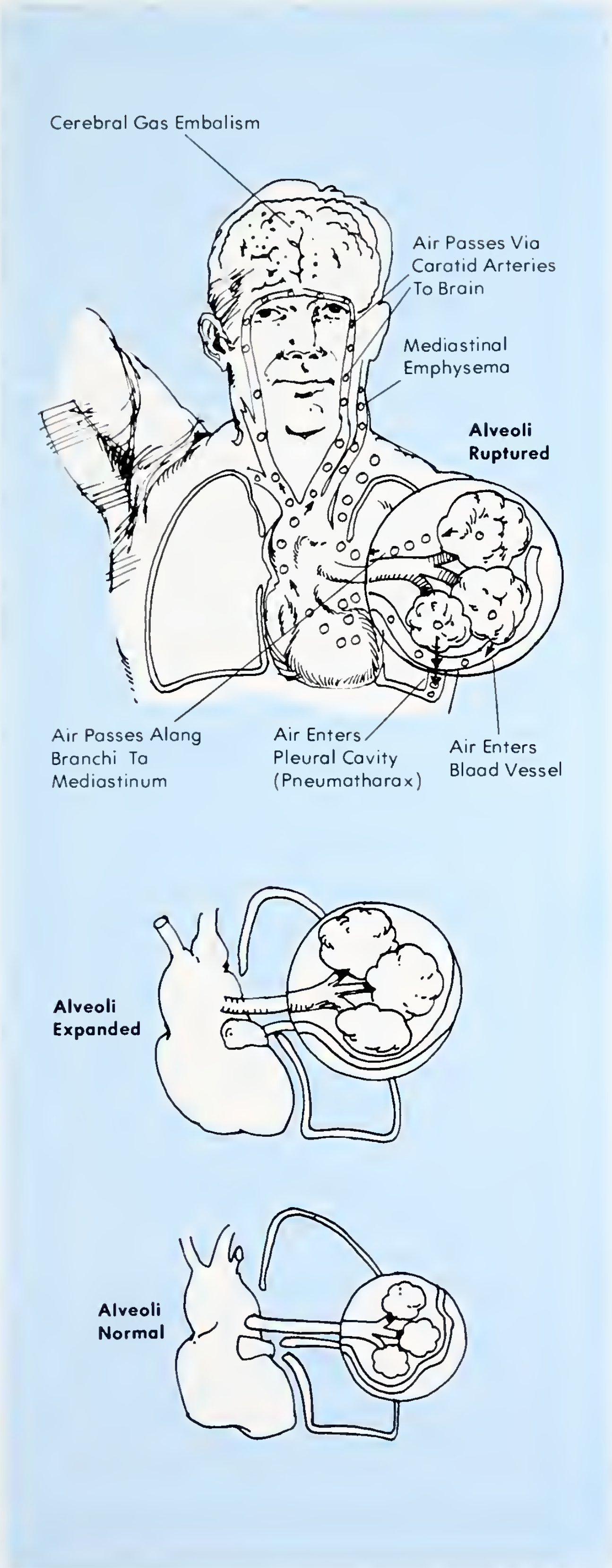
Distended alveoli or air-filled blisters (emphysematous blebs) may rupture the membrane lining of the chest (pleura), causing **pneumothorax**. Under pressure, this is extremely dangerous because trapped intrapleural gas expands as the diver surfaces, causing increased pressure in the chest cavity. The lungs may be collapsed by this pressure, and the heart may be pushed out of its normal position. Symptoms and signs include sudden severe pain, reduction of breathing capability, and, rarely, coughing of frothy blood.

The rapid onset of pneumothorax can cause sudden respiratory and circulatory difficulty, impaired cardiac function, or death from shock. Early diagnosis and prompt treatment with thoracentesis (chest puncture) are essential. If recompression is required for concomitant conditions, the pneumothorax must be vented or released by a chest tube or other device before ascent is accomplished.

3.2.2.2 Mediastinal Emphysema

Mediastinal emphysema is the result of air being forced into the tissues about the heart, the major blood vessels, and the trachea (windpipe) in the middle of the chest. Gas trapped in the spaces between tissues may expand rapidly with continuing decompression, causing impaired venous return. The symptoms of mediastinal emphysema are pain under the sternum (breastbone) and, in extreme cases, shortness of breath or

Figure 3-9
Complications From Expansion of Air in the Lungs During Ascent



Source: NOAA (1979)

fainting caused by circulatory interference resulting from direct pressure on the heart and large vessels. The treatment for mild cases of mediastinal emphysema is symptomatic. In more severe cases, oxygen inhalation may aid resolution of the trapped gas. For severe, massive mediastinal emphysema, recompression is required.

3.2.2.3 Subcutaneous Emphysema

Subcutaneous emphysema, which may be associated with mediastinal emphysema, is caused by air being forced into the tissues beneath the skin of the neck extending along the facial planes from the mediastinum. Unless it is extreme (characterized by a crackling of the skin to the touch), the only symptoms of subcutaneous emphysema are a feeling of fullness in the neck and, perhaps, a change in the sound of the voice. Having the victim breathe oxygen will accelerate the absorption of this subcutaneous air.

3.2.2.4 Gas Embolism

The most serious result of pulmonary overpressurization is the dispersion of alveolar gas into the pulmonary venous system. This gas is carried to the heart and then into the arterial systemic circulation, causing **gas emboli** (gas bubbles) in the coronary, cerebral, and other systemic arterioles. These gas bubbles continue to expand as the pressure decreases, which in turn makes the clinical signs more severe. (Section 20.4.2 describes the symptoms of arterial gas embolism in detail.)

The clinical features of traumatic arterial gas embolism may occur suddenly or be preceded by dizziness, headache, or a feeling of great anxiety. Unconsciousness, cyanosis, shock, and convulsions follow quickly. Motor and sensory deficits occur in various degrees and in different combinations. Death is caused by coronary or cerebral occlusion with cardiac arrhythmia, respiratory failure, circulatory collapse, and shock. Physical examination of a person with a gas embolism may reveal: (1) focal or generalized convulsions; (2) other neurological abnormalities; (3) marbling of the skin; (4) air bubbles in the retinal vessels of the eye; (5) hemoptysis; or (6) Liebermeister's sign (a sharply defined area of pallor in the tongue). Temporary obstruction of an air passage, which can occur with a cold or bronchitis, increases the risk of gas embolism, and diving with a respiratory infection should therefore be avoided. A person with bronchial asthma has hyperreactive small airways in the lung. Breathing dry compressed air, aspiring salt water or cold water, exercising, or being anxious can all cause a bronchospasm under water. Ascent with local air trapped in the alveoli could cause a pressure imbalance and rupture, resulting in gas embolism. For this reason, bronchial asthma is a strict contraindication for compressed gas diving, regardless of how well the asthma is controlled by medication. Coughing or sneezing while in a recompression chamber or while ascending during a dive can also cause a gas embolism. Divers should stop their ascents if they feel a cough or a sneeze coming on, and chamber operators should stop the chamber ascent if they are notified that an occupant of the chamber is about to cough or sneeze.

The only effective treatment for gas embolism is recompression; other treatment is merely symptomatic. A patient should be kept in the head-down position, which may help to keep bubbles in the circulation from reaching the brain. Placing the patient on the left side helps to maintain cardiac output, which may be impaired because the gas bubbles have decreased the efficiency of the pumping action of the heart (see Figure 19-9). In non-fatal cases, residual paralysis, myocardial necrosis, and other ischemic injuries may occur if recompression is not carried out immediately and may even occur in adequately treated patients if there is a delay in initiating therapy. Hyperbaric chambers that cannot be pressurized to 6 ATA are not as effective for embolism treatment as those with this capacity, but recompression to 2 or 3 ATA is far better for the embolism patient than no recompression.

WARNING

Central Nervous System Decompression Sickness Is Clinically Similar to Gas Embolism and the Treatment of Either Requires a Recompression Chamber

In cases of gas embolism, administering oxygen and positioning the body (head-down at a 15 degree angle) are only partially effective; drugs and fluids also may be helpful. These measures should be used in the interval before the patient reaches a recompression chamber (see Section 20.4.2).

3.2.2.5 Overexpansion of the Stomach and Intestine

The stomach and large intestine ordinarily contain 1.06 quarts (1 liter) or more of entrapped gas. Since the intestines are surrounded by soft tissues, the compression and re-expansion of these air bubbles are ordinarily neither hazardous nor noticeable. If one swallows air while diving, it may be necessary during ascent to expel gas by belching or passing it per rectum. An excess of gas in the stomach or intestine during ascent may cause marked discomfort and vasovagal effects. Eating large amounts of gas-producing foods before diving is not recommended. If a diver swallows enough air, he or she may have difficulty breathing and may then panic. Accordingly, activities that cause air swallowing, such as gum chewing, should be avoided during diving.

3.2.2.6 Bubble Formation and Contact Lenses

The use of contact lenses by divers has increased significantly in recent years. For this reason, studies have been done to determine the inherent dangers of using them, especially during decompression (Simon and Bradley 1981). Three types of contact lenses were compared. membrane (soft) lenses and two types of polymethylmethacrylate (hard) lenses. One type of hard lens (fenestrated) had a 0.016 inch (0.4 millimeter) hole in the center, while the other type (non-fenestrated) was solid throughout. During controlled decompressions from 149 feet (45.5 meters) in a hyperbaric chamber, subjects wearing the non-fenestrated hard lenses developed small bubbles in the precorneal tear film under the contact lens. These bubbles, first observed at 70 feet (21.3 meters), increased both in number and size as decompression progressed. The divers wearing these hard lenses experienced soreness, decreased visual acuity, and reported seeing halos when viewing lights. These symptoms were noted at the time of bubble formation and persisted for about 2 hours after return to sea level (Simon and Bradley 1981). No bubbles were noted under the same decompression conditions when the divers wore the fenestrated hard lens, the soft membrane lens, or no lens at all.

The authors of this study concluded that the bubble formation was caused by the lack of permeability of the hard non-fenestrated lens (Simon and Bradley 1981). It is recommended, therefore, that divers electing to wear contact lenses use either soft membrane lenses or hard fenestrated lenses.

3.2.3 Indirect Effects of Pressure

The indirect effects of pressure are caused by changes in the partial pressures of the gases in the breathing medium. These effects include saturation and desaturation of body tissues with dissolved gas and changes in body functions caused by abnormal gas tensions.

3.2.3.1 Inert Gas Absorption and Elimination

While breathing air at sea level, body tissues are equilibrated with dissolved nitrogen at a pressure equal to the partial pressure of nitrogen in the lungs. During exposures to altitude (low pressure) or in diving (high pressure), the partial pressure of nitrogen in the lungs will change and the tissues will either lose or gain nitrogen to reach a new equilibrium with the nitrogen pressure in the lungs. The taking up of nitrogen by the tissues is called **absorption** or uptake; giving up nitrogen from the tissues is termed **elimination**. In air diving, nitrogen absorption occurs when a diver is exposed to an increased nitrogen partial pressure, and elimination occurs when pressure decreases. This process occurs when any inert gas is breathed.

Absorption consists of several phases, including the transfer of inert gas from the lungs to the blood and then from the blood to the various tissues through which it flows. The gradient for gas transfer is the partial pressure difference of the gas between the lungs and blood and the blood and the tissues. The volume of blood flowing through the tissues is usually small compared to the mass of the tissue, but over a period of time the gas delivered to the tissue will cause it to become equilibrated with that carried in solution by the blood. The rate of equilibration with the blood gas depends on the volume of blood flow and the respective capacities of blood and tissues to absorb the dissolved gas. For example, fatty tissues hold significantly more gas than watery tissues and will thus take longer than watery tissues to saturate or desaturate excess inert gas.

The process of elimination is the reverse of absorption. During ascent and after surfacing, the tissues lose excess inert gas to the circulating blood by diffusion, the gradient being the difference between the inert gas partial pressure in each tissue and that in the blood after the blood has equilibrated to the pressure of the gas in the lungs. The amount of inert gas that can be taken up in the blood is limited, so the tissue inert gas tension falls gradually. As in absorption, the rate of blood flow, the difference in partial pressures, and the amount of inert gas dissolved in the tissues and blood determine the rate of elimination. After decompressing to the surface or ascending to a shallower level, equilibration at the new level may require 24 hours or more.

It is assumed that, during decompression, the blood and tissues can to some degree hold gas in supersaturated solution without bubbles being formed. A supersaturated solution is one that holds more gas than would be possible at equilibrium at the same temperature and pressure. Because of the ability of the blood and tissue to become supersaturated for short periods of time, a diver can ascend a certain distance, depending on the depth and duration of his or her dive, without bubble formation. The ascent establishes an outward gradient and thus causes inert gas to be eliminated from body tissues; after a sufficient time, enough gas will have been eliminated to permit the diver to ascend further. This process is continued until the diver reaches the surface safely. On surfacing, the diver's body still contains inert gas in supersaturated solution in some tissues, but this is normally safe if kept within proper decompression limits and if further pressure reduction, such as ascent to altitude, does not occur (see Section 14.8).

The basic principles of absorption and elimination are the same for any inert gas breathed. However, there are differences in the solubility and rates of gas diffusion in water and fat. Helium is much less soluble in tissues than nitrogen and diffuses faster. Thus, helium equilibration occurs somewhat more rapidly than is the case for nitrogen. The advantages in using helium-oxygen rather than nitrogen-oxygen mixtures are freedom from narcosis and a decrease in breathing resistance.

To develop mathematical models of gas solubility in tissues, physiological theory postulates that the human body is composed of several 'tissue compartments,' each having a different 'half time.' For example, a compartment with a half time of 10 minutes is one in which the tissues are 50 percent saturated with gas after exposure to pressure for 10 minutes, while a 20-minute compartment would be 50 percent saturated in 20 minutes, and so on. Various characteristics of these theoretical compartments, such as their relative fattiness, are believed to account for these differences in tissue half times.

3.2.3.2 Decompression Sickness

Decompression sickness (DCS) refers to the illness that may occur after a reduction in barometric pressure; such a reduction in pressure can occur either when returning from the depth of a dive to the atmosphere at sea level or when going from the atmosphere at sea level to the atmosphere at altitude. The cause of decompression sickness is the release of dissolved gas from solution in the tissues and blood of the body and the consequent formation of bubbles in the body. That bubbles are the cause of DCS is borne out by the facts that (1) bubbles have been seen and recorded during incidents of DCS (as well as during decompressions in which no DCS symptoms occurred), and (2) no other explanation accounts so well for the success of recompression therapy as a treatment for DCS.

These bubbles can cause the symptoms and signs of DCS through various mechanisms: Intracellular bubbles can disrupt the cells and cause loss of function; intravascular bubbles can act as emboli and block circulation either to a few or many tissues, depending on where these bubbles lodge; and extravascular bubbles can cause compression and stretching of the blood vessels and nerves. In addition, the blood-bubble interface acts as a foreign surface and activates the early phases of blood coagulation and the release of vasoactive substances from the cells lining the blood vessels.

The causes of DCS include inadequate decompression (either because the decompression table used was inadequate or was not followed properly), individual physiological differences, or environmental factors. Inadequate decompression is an obvious cause of DCS, but frequently no symptoms occur even when the decompression is obviously inadequate. In addition, decompression sickness may occur even if the decompression tables used are adequate and are strictly observed. Moreover, it is common to assume that DCS cannot occur on a 'no-decompression' dive; however, although it is uncommon for DCS to occur on no-decompression dives, it can happen. Differences in individual physiology that may predispose to DCS include factors such as obesity, fatigue, age, poor physical condition, being dehydrated, or having an illness that affects the lung or circulatory efficiency. Environmental factors that have been implicated in the development of DCS are cold water, heavy work, rough sea conditions, and the use of heated suits.

Decompression sickness (colloquially termed 'the bends') may be divided into two general categories, Type I and Type II. Type I DCS includes those cases in which pain, skin itching or marbling, or lymphatic involvement are the only symptoms. The mildest cases of DCS are those involving the skin or the lymphatics. Skin bends are characterized by itching of the skin and a burning sensation, which may also be accompanied by the appearance of a mottled rash or marbling of the skin. Lymphatic involvement is usually signaled by painless swelling, but such involvement is uncommon. Some experts also consider the symptoms of anorexia and excessive fatigue that may follow a dive manifestations of Type I DCS. In addition, 'niggles,' which are mild pains that begin to resolve within 10 minutes of onset, are considered symptoms of Type I DCS. These mild cases of Type I DCS (skin bends, lymphatic involvement, or niggles) do not require treatment other than breathing pure oxygen at 1 ATA for a short period of time, and often even this is not required. However, any diver with niggles, skin bends, or lymphatic involvement should be watched closely, because these symptoms may presage the onset of more serious problems that will require recompression. It should not simply be assumed that these symptoms will not progress to more severe ones.

The most common symptom of DCS is pain, which is usually localized at a joint. Pain is reported to occur in 70 to 75 percent of DCS cases. The pain of DCS is often described as a dull, throbbing pain deep in the joint or tissue. The onset of this pain is usually gradual and, in the early stages, the diver may not recognize the pain as being related to DCS. However, the pain slowly becomes more intense and, in some cases, it may become severe enough to interfere with the strength of the limb. In divers, the upper limbs are affected about three times as often as the lower limbs. Before it is decided that the case involves Type I DCS only, the diver should be given a careful examination for any neurological signs, because the pain may be masking more serious symptoms. However, if pain is truly the only symptom, the case falls into the Type I category and should be treated as such.

Although pain is reported as a symptom in 30 percent of cases of Type II DCS, this form of DCS includes all cases that have respiratory problems, hypovolemic shock, or more serious symptoms or signs of central or peripheral nervous system involvement. Because of the involvement of the nervous system, Type II DCS may be associated with many different signs and symptoms. These usually have their onset during or immediately after a dive but, as is the case with Type I DCS, may occur as long as 36 hours after surfacing. The most common site for Type II DCS is the spinal cord, and the most common symptoms are similar to those seen in spinal cord trauma; these include paralysis, loss of sensation, muscular weakness, loss of sphincter control, and girdle pain of the trunk. Often the symptoms or signs of either spinal cord DCS or peripheral nerve DCS do not follow a typical nerve distribution, and care must be taken not to dismiss strange neurological complaints or findings as hysterical in origin. Symptoms may be unstable in position and type during the early stage of spinal or peripheral DCS; this shifting in symptoms is different from the usual history of traumatic nerve injuries.

Cerebral decompression sickness can be manifested in the form of almost any symptom. Common ones are headaches or visual disturbances, and others include dizziness, tunnel vision, confusion, disorientation, psychotic symptoms, and unconsciousness. The combination of nausea, vomiting, vertigo, and nystagmus is characteristic of labyrinthine DCS, which is known as the 'staggers' because its victims have difficulty walking or maintaining their balance. Tinnitus and partial deafness may also occur as part of this complex of symptoms.

Pulmonary DCS is commonly known as the 'chokes.' It is characterized by substernal distress on inhalation, coughing that can become paroxysmal, and severe respiratory distress that can end in death. This form of DCS has been reported to occur in about 2 percent of all DCS cases.

Hypovolemic shock may occur as the sole symptom of Type II DCS, but it is more commonly associated with other symptoms. The symptoms of rapid pulse rate, postural hypotension, etc., are no different from those found in hypovolemic shock occurring for other reasons and should be treated in the same manner, that is, by rehydration. Rehydration should be performed orally if the patient is conscious or, if unconscious, intravenously. Mild hypovolemia may be more common in diving than is generally realized because of the increased heat load that results from working hard while dressed in a diving suit, limited access to fluids, pressure or cold diuresis, etc. Hypovolemic shock should always be identified and treated, because the treatment of DCS is less effective if the shock condition has not been corrected. A more complete discussion of the symptoms of DCS may be found in Elliott and Kindwall (1982).

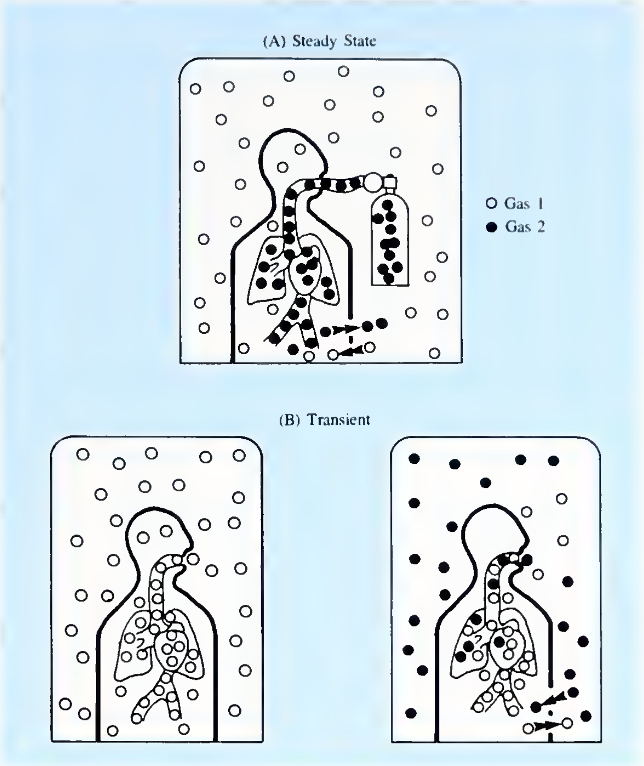
3.2.3.3 Counterdiffusion

Experiments dating back to 1962 have demonstrated that the sequential use of different breathing gases in a particular order, determined by their physical properties, could increase dive time at depth without increasing a diver's decompression obligation. During some of these experiments, however, it was discovered that a diver breathing one gas mixture while surrounded by another could develop serious gas lesions even when the ambient pressure was maintained at a constant level (D'Aoust and Lambertsen 1982).

For example, experimental subjects breathing neon or nitrogen mixtures while surrounded by a helium environment developed skin lesions, severe nausea, vomiting, and vestibular derangement. Because this phenomenon involves the passage of gases at the same ambient pressure through tissue fluids in opposing directions, it has been termed **isobaric counterdiffusion** or **isobaric counterexchange**.

Depending on circumstances, **counterdiffusion** (supersaturation or subsaturation) can occur in the skin or between internal tissues and their capillaries. This can lead not only to serious lesions but also to the formation of gas emboli even when ambient pressures are constant. The process is shown in Figure 3-10. The situation depicted in Figure 3-10A is referred to as 'steady state' and occurs when the superficial tissues of the subject approach saturation with gas 2 (•) except at the skin, where a gradient sloping to the exterior exists; note that the superficial skin approaches saturation with gas 1 (◦), except for a gradient in gas 1 that slopes from the exterior to the interior blood capillaries. The process depicted in Figure 3-10B occurs in deep tissue isobaric gas exchange. Deep-tissue isobaric counterdiffusion occurs if the gas surrounding a diver is suddenly changed to one that is different from the one being breathed. In such a situation, gas 1 (◦) will be eliminated via the lungs and initially through the skin, and gas 2 (•) will be taken up again via the lungs and through the skin. Unlike the situation in Figure 3-10A, this latter process must be considered transient, since gas 1 (◦) eventually will be reduced to a negligible level and gas 2 (•) will eventually saturate the subject at a final pressure that is no greater than ambient (D'Aoust and Lambertsen 1982).

Figure 3-10
Isobaric Counterdiffusion



Source: Bennett and Elliott (1982), with the permission of Bailliere Tindall, Ltd.

Depending on depth and the breathing gases being used, the total gas tensions produced during the transient can reach levels sufficiently high to cause bubble formation and decompression sickness. Work in this complex field is continuing and should lead to the use of improved gas sequences and improvement in the efficiency of deep diving and the development of safer decompression procedures.

3.2.3.4 Aseptic Bone Necrosis (Dysbaric Osteonecrosis)

Exposure to compressed air at elevated atmospheric pressure is sometimes associated with the death of portions of the long bones of the exposed individual. This condition is referred to as avascular necrosis of bone, caisson disease of bone, or **aseptic** or **dysbaric bone necrosis**. These changes are not of infectious origin, and they have been seen in patients suffering from many conditions, such as chronic alcoholism, pancreatitis, and sickle-cell anemia, in patients using systemic steroids, and in caisson (compressed air tunnel) workers and divers. The development of changes in the hip and shoulder joints of caisson workers, accompanied by crippling effects caused by joint breakdown, was first noted in 1888, but the disease has not been particularly prevalent in divers, who generally observe more conservative decompression procedures than compressed air tunnel workers do.

If the lesions of aseptic bone necrosis occur in the head of such bones as the femur (long leg bone) or humerus (bone of the upper arm), the weakened underlying bone that supports the cartilage covering the bone will collapse under weight-bearing and activity, causing the joint surface to break down and become irregular. Pain occurs with movement of these joints and is accompanied by muscle spasms around the joint and the inability to use the joint in a normal manner. Since the lesions often are bilateral and symmetrical, both femoral heads may collapse, causing severe disability.

Lesions may also occur in the shafts of the long bones, but these almost never cause symptoms or disability; however, bony scars that indicate increased density may appear on x ray after new bone is deposited during the healing process. Bone necrosis is seldom seen in the elbows, wrists, or ankles of divers or caisson workers (Kindwall 1972).

Factors that may be related to the likelihood of developing bone lesions are frequency of exposure to pressure, number of cases of bends, adequacy and promptness of recompression treatment, and the total amount of exposure to pressure. According to McCallum and Harrison (1982), "The whole process from the first radiographic appearance of the lesions to loss of continuity in the joint surface may take only from 3 or 4 months to 2 or 3 years or perhaps longer."

The cause of aseptic bone necrosis has still not been demonstrated beyond doubt. There is some evidence that fat emboli may occlude circulation in the blood vessels in bone and other tissues and thus may be a factor in the development of hip lesions in the chronic alcoholic with a fatty liver. In patients with gout, lesions of the hip joints have contained sodium urate crystals, which may have been a factor in the destruction of the joint surface. Bone lesions may not become apparent on x rays for 4 months to 5 years after the initiating insult. A detailed review of aseptic bone necrosis may be found in McCallum and Harrison (1982).

A 3-year survey of 350 full-time divers in the British Navy showed a 5-percent incidence of aseptic bone necrosis; half of the affected divers had shown no evidence of having experienced decompression sickness (Workman, personal communication). In a recent survey of 934 U.S. Navy divers, 16 positive cases of aseptic bone necrosis were found by standard radiographic techniques; another 11 cases were interpreted as doubtful (Hunter et al. 1978). The data revealed a 1.71 percent incidence overall and a 6.7 percent incidence for divers over the age of 35. Although the relationship between aseptic bone necrosis and decompression sickness is not clear, the incidence of osteonecrosis in the subjects of this study was found to be related both to age and number of months of diving.

In another study conducted by the U.S. Navy, the long-bone radiographs of a group of 177 non-diving enlisted men were compared to the long-bone radiographs of 93 enlisted divers 35 years of age or over (Hunter and Biersner 1982). It was found that diving, as practiced by the U.S. Navy, contributes independently to the development of aseptic bone necrosis and bone cysts, as evidenced among divers in the tested group. This conclusion was qualified by the statement that the results must be viewed with caution 'because of the larger number of doubtful films found for the nondiver group than for the diver group, the small number of positive and doubtful cases found in either group, the age of the samples used (35 years of age or older), and the substantial degree of unreliability demonstrated in the classification of the films' (Hunter and Biersner 1982). A subsequent study, also by the U.S. Navy, concluded that the prevalence of bone cysts among Navy divers is probably related to one or more of several conditions, including hyperbaric exposure, genetic predisposition, and increased exposure to adverse environmental or hazardous conditions (Biersner and Hunter 1983).

3.2.3.5 Inert Gas Narcosis

Inert gas narcosis is caused by the raised partial pressure of the inert gas in compressed air (see Section 20.1.6). In diving, the most common type of inert gas narcosis is nitrogen narcosis. Although nitrogen and other inert gases are physiologically inert under normal conditions, they are able to induce signs and symptoms of narcosis or anesthesia at sufficiently raised pressures. Other inert gases, such as those in the noble gas series, range in narcotic potency from helium through neon, nitrogen, argon, and krypton to the surgical anesthetic xenon. Recent analyses have demonstrated that the qualitative behavioral effects are equivalent regardless of the specific gas causing the narcosis (Fowler et al. 1985). Neon has been used satisfactorily for experimental diving procedures but is not used in diving today. Helium is a gas widely used in diving as a substitute for nitrogen and to prevent narcosis (see Section 15.1.3). Helium is such a weak narcotic that helium narcosis has not been demonstrated.

Although many theories have been developed to explain the mechanism of inert gas narcosis, it is clear that it is caused by the physiochemical interaction of the inert gas with the nerve cell membranes of the body. A theory widely held that has been proved incorrect is that the signs and symptoms of narcosis are caused by carbon dioxide retention resulting from respiratory embarrassment occasioned by the breathing of dense inert gas mixtures at raised pressures.

The signs and symptoms of narcosis are noticed first at approximately 100 feet (30.5 meters) during compressed air breathing and are similar to those of alcoholic intoxication or the early stages of hypoxia; there is a wide variation in individual susceptibility. However, at greater depths the majority of compressed air divers show impairment of thought, time perception, judgment, reasoning, memory, ability to perform mental or motor tasks, and increased reaction time (see Table 3-2). Many measures have been used to assess the performance decrement resulting from inert gas narcosis. Cognitive tests are more sensitive measures of narcotic effects than manual dexterity tests (Fowler et al. 1985). Intellectual capacities such as short-term memory are affected to a greater extent than manual dexterity. If divers expect to dive in situations where they are likely to become narcotic, they should practice anticipated tasks well before diving.

Divers experiencing nitrogen narcosis may have feelings of elation and well-being (euphoria) and a sense of detachment from the environment, accompanied by a dangerous overconfidence, an uncontrollable desire to laugh, and a tingling and vague numbness of the lips, gums, and legs. There may be an inability to make correct and rapid decisions or to concentrate effectively on a task. Errors may be made in recording or compiling data or computations. Novices, especially, may develop terror rather than euphoria. Narcosis is a significant danger to divers because it increases the risk of an accident and simultaneously diminishes their ability to cope with an emergency.

The onset of narcosis is rapid. The condition is often severe when a diver first reaches depth and may thereafter stabilize. Recovery is equally rapid and is accomplished by ascending to a shallower depth so that the narcotic effect of the inert gas is reduced. Divers who have experienced narcosis on a dive may not remember events occurring at depth.

High alveolar pressures of N_2 and CO_2 are additive in their effects on performance, but CO_2 has no significant effect on nitrogen narcosis (Hesser, Adolfson, and Fagraeus 1971). Factors that can increase the susceptibility to narcosis include alcohol or the aftereffects of alcohol, fatigue, anxiety, cold, and the effects of motion sickness remedies and sedatives. At a constant nitrogen partial pressure, increases in the oxygen partial pressure increase the signs and symptoms of narcosis (Hesser 1963; Frankenhaeuser et al. 1960).

For air dives to depths greater than 100 feet (30.5 meters), special precautions should be taken; only experienced, fit, and well-trained divers should be used. As many decisions as possible should be made before the dive, including length of bottom time, duration of ascent, and actions to be taken in an emergency.

Experience, frequent exposure to deep diving, and a high degree of training may permit divers to dive as deep as 180-200 feet (54.9-61 meters) on air, but novices or susceptible individuals are advised to remain at shallower depths. At depths greater than 180 feet (54.9 meters), the performance or efficiency of divers breathing compressed air will be impaired. At 300 feet (91.5 meters) or deeper, the signs and symptoms of narcosis are severe and there is the possibility of hallucinations, bizarre behavior, or loss of consciousness. Furthermore, because of the associated increased oxygen partial pressure at such depths, oxygen convulsions may occur.

Experimental work has suggested that divers saturated on compressed air or a mixture of nitrogen and oxygen tend to adjust to some of the narcotic effects of nitrogen, thus permitting deeper air breathing excursions to be made (Hamilton et al. 1973, Schmidt et al. 1974, Langley and Hamilton 1975, Miller 1976). However, divers must have demonstrated their ability to adjust to elevated partial pressures of nitrogen before procedures relying on it can be used without taking extra care and providing additional supervision (Bennett 1976, 1982). Various efforts have been made to use drugs and other methods to reduce the effects of narcosis. In general, 'the weight of evidence favors the conclusion that ethanol (alcohol) exacerbates narcosis and amphetamine ameliorates it. This is consistent with the view that narcosis depresses the CNS (central

Table 3-2
Narcotic Effects of
Compressed Air Diving

Depth		
Feet	Meters	Effect
30-100	9.1-30.5	Mild impairment of performance on unpracticed tasks Mild euphoria
100	30.5	Reasoning and immediate memory affected more than motor coordination and choice reactions. Delayed response to visual and auditory stimuli
100-165	30.5-50.3	Laughter and loquacity may be overcome by self control Idea fixation and overconfidence Calculation errors
165	50.3	Sleepiness, hallucinations, impaired judgment
165-230	50.3-70.1	Convivial group atmosphere. May be terror reaction in some Talkative. Dizziness reported occasionally Uncontrolled laughter approaching hysteria in some
230	70.1	Severe impairment of intellectual performance. Manual dexterity less affected
230-300	70.1-91.5	Gross delay in response to stimuli. Diminished concentration Mental confusion. Increased auditory sensitivity, i.e., sounds seem louder
300	91.5	Stupefaction. Severe impairment of practical activity and judgment Mental abnormalities and memory defects. Deterioration in handwriting, euphoria, hyperexcitability Almost total loss of intellectual and perceptive faculties
300	91.5	Hallucinations (similar to those caused by hallucinogenic drugs rather than alcohol)

Derived from Edmonds, Lowry, and Pennefather (1976)

nervous system)' (Fowler et al. 1985). (Readers are referred to Bennett (1982) and Fowler et al. (1985) for more complete discussions of inert gas narcosis.)

3.2.3.6 High Pressure Nervous Syndrome (HPNS)

At diving depths greater than 600 fsw (183 msw), signs and symptoms of a condition known as the **high pressure nervous syndrome** (HPNS) appear and become worse the faster the rate of compression used and the greater the depth or pressure attained. HPNS is characterized in humans by dizziness, nausea, vomiting, postural and intention tremors, fatigue and somnolence, myoclonic jerking, stomach cramps, decrements in intellectual and psychomotor performance, poor sleep with nightmares, and increased slow wave and decreased fast wave activity of the brain as measured by an electroencephalogram (Bennett et al. 1986).

First noted in the 1960's, HPNS was referred to initially as helium tremors. Since that time, numerous studies have been conducted that were designed to determine the causes of HPNS and to develop means of preventing it (Bennett 1982). Methods of preventing or ameliorating HPNS include using a slow and steady rate of compression to depth, using a stage compression with long pauses at selected intervals, employing exponential compression rates, adding other inert gases such as nitrogen to helium/oxygen mixtures, and selecting personnel carefully. At present, the data suggest that adding 10 percent nitrogen to a helium/oxygen mixture, combined with the use of a proper compression rate, ameliorates many of the serious symptoms of HPNS (Bennett 1982).

3.3 OXYGEN POISONING

Prolonged exposure to higher than normal oxygen partial pressures causes a variety of toxic effects whose manifestations are referred to collectively as **oxygen poisoning**. It is now believed most likely that oxygen poisoning is initiated by increased rates of formation of superoxide, peroxide, and other oxidizing free radicals that ultimately cause critical enzyme inactivation, lipid peroxidation, and impairment of cell membrane function, with resultant disruption of intracellular metabolism. These adverse effects of oxidant species are opposed by anti-oxidant protective mechanisms until the defenses are overwhelmed by the magnitude and duration of oxidant stress. Thus, the onset time, nature, and severity of overt manifestations of oxygen toxicity are determined by the inspired oxygen pressure and duration of exposure, as well as by unique characteristics of enzyme function and external manifestations of specific disruptions of intracellular metabolism. Since oxygen toxicity is a generalized phenomenon that affects all living cells, its adverse effects are ultimately expressed in all organ systems and functions (Lambertsen 1978).

Pulmonary oxygen poisoning will occur during prolonged exposure to any oxygen partial pressure above 0.5 atmosphere. At the lower end of this range, detectable degrees of pulmonary intoxication would occur only after many days to weeks of saturation exposure (Clark and Lambertsen 1971a). During continuous administration of 100 percent oxygen, pulmonary symptoms have been observed within 12 to 24 hours at 1.0 atmosphere (Comroe et al. 1945), 8 to 14 hours at 1.5 atmosphere (Clark et al. 1987), 3 to 6 hours at 2.0 atmospheres (Clark and Lambertsen 1971b), and 1 to 3 hours at 3.0 atmospheres (Clark et al. 1987). The onset of symptoms is usually characterized by mild substernal irritation that intensifies slowly at first and then more rapidly until each inspiration is painful. Coughing also progressively increases in severity until it cannot be suppressed after deep inspiration. Shortness of breath during exertion, or even at rest, may occur in severe exposures, presumably because of decreased vital capacity, which can occur before symptoms are obvious.

Central nervous system (CNS) oxygen poisoning culminating in generalized convulsions followed by unconsciousness is a dominant manifestation of oxygen intoxication during exposures to oxygen partial pressures above 2.0 atmospheres. Convulsions may also occur while breathing oxygen at lower partial pressures during periods of exertion, particularly when combined with underwater immersion, during periods of carbon dioxide accumulation with concurrent increments in cerebral blood flow and brain oxygen tension, and in unusually susceptible individuals. Muscular twitching, especially of the face and lips, or hands, may precede the onset of convulsions. When this sign does occur, it should serve as a warning to reduce the inspired oxygen pressure or to terminate the oxygen exposure immediately, if possible.

In a group of 18 normal resting men breathing oxygen for up to 3.5 hours at 3.0 atmospheres in a hyperbaric chamber, constriction of peripheral vision always occurred prior to convulsions (Lambertsen et al. 1987). Nausea and dizziness may occur intermittently during continuous oxygen exposure. Other symptoms or signs of CNS oxygen poisoning include ringing in the ears, irregularities in breathing pattern, diaphragmatic spasms, muscular incoordination, fatigue, confusion, and anxiety. Extreme bradycardia to a degree sufficient to cause cerebral ischemia with transient loss of consciousness may occur during prolonged oxygen exposure at 3.0 atmospheres (Pisarello et al. 1987).

Oxygen effects on organs other than the lungs and CNS undoubtedly occur to some degree during exposures that produce overt manifestations of pulmonary or neurologic oxygen poisoning (Clark 1983, Lambertsen 1978). These effects go unnoticed because they are not associated with chest pain, convulsions, or other obvious indications of oxygen poisoning. Although the nature and degree of such effects are not now known, likely target sites include the liver, kidney, endocrine organs, and hematopoietic tissues. In addition, a regular increase in myopia (near-sightedness) has been noted in some patients who receive daily hyperbaric treatments (Lyne 1978, Anderson and Farmer 1978). Individuals exposed to elevated partial pressures of oxygen in saturation diving conditions also have been found to experience potent visual effects (Kinney 1985).

In the absence of definitive information regarding the subtle effects of oxygen toxicity, it is important to remain aware that organ systems and functions external to the lungs and CNS may be adversely affected by either prolonged and continuous or repeated and intermittent oxygen exposures. It is likely that such effects would be most evident either near the end of a continuous oxygen exposure or within several hours after exposure termination. During a series of intermittent oxygen exposures, the probability of detection of subtle adverse effects will increase directly with the number and duration of exposures.

In humans, recovery from oxygen poisoning after oxygen pressure-exposure duration combinations that do not produce overt intoxication appears to be sufficiently complete to allow appropriately spaced, repeated exposures without fear of cumulative or residual effects (Lambertsen 1978). Full recovery from such conditions probably requires relatively limited and rapid reactivation of critical enzymes and reversal of early alterations in cellular function. When overt manifestations of oxygen poisoning are produced, however, recovery probably requires a more extensive and lengthy reversal of tissue inflammatory reactions and repair of cellular metabolic or structural defects.

Rates of recovery from the symptomatic and functional effects of oxygen toxicity are variable for different effects and different individuals. The complete resolution of most symptoms associated with CNS oxygen poisoning occurs within minutes after the inspired oxygen pressure is reduced to normal levels. Even after an oxygen convulsion, recovery can occur within 30 minutes, but it may require an hour or more in some individuals. Chest pain and cough associated with oxygen-induced tracheobronchitis usually resolve within 2 to 4 hours after exposure termination, but unusual fatigue and mild dyspnea on exertion may occasionally persist for several days or even a few weeks after exposure. Although there is a wide range in individual variability, oxygen-induced deficits in vital capacity and forced expiratory and inspiratory flow rates typically reverse within 1 to 3 days after exposure, while recovery of pulmonary diffusing capacity for carbon monoxide often requires 1 to 2 weeks or more (Clark et al. 1987).

Hyperoxic exposures for diving and decompression applications should be planned to remain well within the known oxygen tolerance limits. They should also be appropriately spaced to ensure complete recovery between exposures. This approach will both avoid the cumulative, residual effects of oxygen poisoning and maintain a reserve of oxygen tolerance in case hyperoxygenation therapy is required for decompression sickness or gas embolism. If (as might occur in a complex treatment) oxygen therapy makes it necessary to cause a significant degree of pulmonary intoxication in a patient, subsequent operational exposures to hyperoxia should be delayed for at least several weeks to allow complete recovery.

A variety of conditions, procedures, and drugs can be used to modify the oxygen tolerance of humans (Clark and Lambertsen 1971a). These factors may affect the time of onset, rate of progression, or severity of one or more of the diverse manifestations of oxygen poisoning. Of all the factors known to hasten the development of oxygen poisoning, the effects of exercise and carbon dioxide accumulation are most relevant to diving operations.

By mechanisms that are not well understood (apart from the possible influence of concurrent carbon dioxide retention), physical exertion itself exacerbates the development of CNS oxygen poisoning. This reduction in CNS oxygen tolerance is expressed both by the earlier onset of convulsions at oxygen pressures above 2.0 atmospheres and by the occurrence of convulsions during exposure to oxygen pressures at which oxygen-induced seizures would otherwise almost never occur in normal, resting individuals. The adverse effects of exercise on pulmonary or other non-neurologic manifestations of oxygen intoxication have not been demonstrated.

Elevated arterial carbon dioxide pressure will also hasten the onset of convulsions or cause them to occur at unusually low oxygen pressures. Possible causes of carbon dioxide retention include faulty CO_2 absorption in closed-circuit breathing equipment, inadequate pulmonary ventilation while exercising under conditions of excessive external resistance to breathing, and intentional hypoventilation to conserve air. Cerebral vasodilation, which occurs in response to carbon dioxide retention, is responsible for the prominent elevation of brain oxygen tension during oxygen breathing and accounts for most, if not all, of the associated decrement in CNS oxygen tolerance.

Extending human oxygen tolerance by means of drugs that have been shown to delay one or more manifestations of oxygen toxicity has not to date been shown to be practical. Since such an agent ideally would have to be distributed throughout all body tissues and oppose toxic effects on a variety of enzymatic targets, it is not likely that any drug now available will ever have more than a limited potential for practical application (Clark 1983, Lambertsen 1978). At the present time, the most useful procedure for extending human oxygen tolerance employs systematic alternation of hyperoxic and normoxic exposure intervals to increase greatly the tolerable duration of exposure to a selected level of hyperoxia. This procedure takes practical advantage of the empirical observation that many early, subclinical effects of oxygen toxicity are reversed more rapidly than they develop. Interrupted exposure as a means of oxygen tolerance extension was initially studied in animals (Clark 1983, Lambertsen 1978), and its effectiveness was later demonstrated directly in man (Hendricks et al. 1977). Although periodic interruption of oxygen exposure has been a component of the U.S. Navy oxygen treatment tables (US Navy 1985) for many years, its potential for oxygen tolerance extension has been only minimally exploited to date.

3.4 EFFECTS OF COLD (HYPOTHERMIA)

Hypothermia is a condition in which the deep tissue or core temperature of the body falls below 95°F (35°C), which is the temperature at which malfunctions in normal physiology begin to occur. If the core temperature drops below 96.8°F (36°C), diving operations should be terminated because the consequences of continuing are serious. If the core temperature falls to 93.2°F (34°C), temporary amnesia may occur and emergency rewarming and medical treatment are required. Between 86° and 89.6°F (30° and 32°C), cardiac irregularities commence and unconsciousness may result.

Because water has a specific heat approximately 1000 times greater than that of air and a thermal conductivity 24 times greater than that of air, the body loses heat much faster in water than in air of the same temperature. Fortunately, the thermoregulatory system of the body is highly sensitive to stimulation from the hands and feet, so that the body's heat generating systems are activated before the core temperature is affected seriously. The fact that the hands and feet get cold first is thus, in this sense, an advantage.

With cold skin and with core temperatures below 96.8°F (36°C), the defense mechanisms of the body are activated. These mechanisms consist of shivering, which can increase basal body heat production by up to five times, and vasoconstriction, which reduces blood flow to the periphery and thus reduces heat loss. Unfortunately, these mechanisms rarely achieve heat balance, so that the diver continues to lose heat.

In addition to losing body heat by conductive loss from the skin, a significant loss (10 to 20 percent of total body heat loss) occurs by evaporation from the lungs. The percentage is dependent on the humidity of the inspired air, since the drier the air the greater the evaporative heat loss. Further, as divers go deeper and their breathing gas becomes more dense, convective heat loss increases. Breathing gas heating is needed beyond depths of 400 feet (122 meters).

3.4.1 Thermal Protection

Obviously, a diver exposed to cold water or even moderately warm water for long periods must wear protective clothing. Because of large individual differences in cold tolerance, every diver must determine the most suitable protection on an individual basis. A variety of diving suits is available, ranging from standard foamed neoprene wet suits and dry suits to specially heated suits (for detailed descriptions of these suits, see Sections 5.4 and 10.8).

The use of protective equipment, however, creates a complication because the body's defense mechanism is modified by the thermal barrier of the clothing. This complication is only just being recognized as important, and divers should be aware that the faster the rate of heat loss, the smaller the drop in core temperature for a given quantity of heat loss. Furthermore, whether or not a person shivers is strongly influenced by: (1) the rate of body heat loss; (2) the amount of body fat; and (3) the body size. Larger, fatter people are less affected by a given cold exposure and less affected by a given amount of heat loss. For example, because heat transfer is about 100 to 200 times faster in water than in air, the heat that reaches the skin surface is rapidly transferred to the water. Generally, the thicker the layer of subcutaneous fat, the greater the insulation.

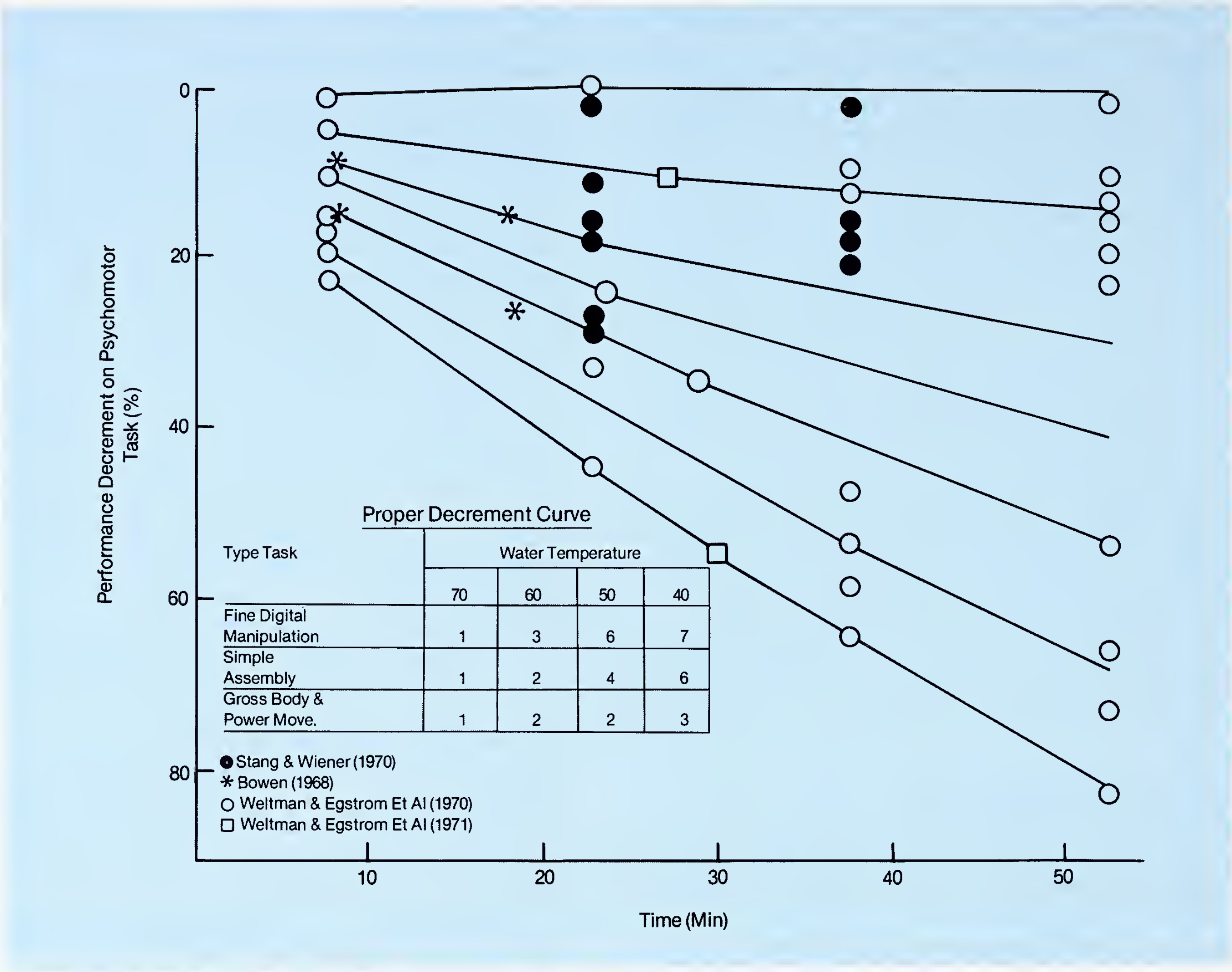
During swimming, the increase in energy production resulting from exercise is counterbalanced by the increase in muscle blood flow resulting in greater heat transfer. Thus swimming promotes faster transfer of heat from the core to the periphery, and this heat is in turn lost to the water (Nadel 1984). This is why persons suddenly immersed in cold water or divers becoming cold are better off remaining still than trying to swim. Rapid heat loss provokes strong shivering, so that the diver is warned. Gradual heat loss over a long time often will not cause shivering, yet the accumulated cooling and the likelihood of hypothermia may be even greater, with the likely result of impaired performance. Use of apparently adequate thermal protection in prolonged dives, or repeated dives over several days, may produce long slow cooling and undetected hypothermia even in tropical water. This affects memory and the speed of reasoning and other cognitive functions, thus reducing a diver's effectiveness and possibly endangering him or her. In addition, repeated diving with inadequate thermal protection may lead to an unwillingness to dive again or to disabling fatigue—states that are now known to be associated with being cold (Webb 1985).

3.4.2 Symptoms of Hypothermia

It is easy to recognize that hands and feet are cold by the familiar sensations of discomfort, numbness, pain, and diminished usefulness. On the other hand, loss of body heat is extremely difficult to recognize. Individuals are poor judges of their own thermal state. As body heat is lost, the body approaches **hypothermia**; recognizing hypothermia in its early stages is a serious problem in diving. Deep hypothermia, meaning a rectal temperature of 95°F (35°C) or lower, is dangerous; at this stage, a diver may become helpless.

Chilling, even if not severe enough to threaten life, will produce loss of dexterity and sense of touch in the hands, making it difficult for a diver to do useful work or even to control diving equipment such as weight belts and buoyancy compensators. Shivering causes a lack of coordination and may make it difficult for a diver to hold the mouthpiece in place. By the time shivering becomes uncontrollable, oxygen consumption has increased significantly. Before this, however, the dive should have been terminated and rewarming started. The ability to think clearly and short-term memory also may be affected seriously by cold. Figure 3-11 shows the effect of cold water on psychomotor performance when a diver is wearing a 1/4-inch (0.63 centimeter) wet suit, with hood, gloves, and booties. For example, both fine digital manipulation and the execution of a simple assembly task are affected

Figure 3-11
Effect of Exposure Duration on
Psychomotor Task Performance
in Cold Water



Proper Decrement Curve

Type Task	Water Temperature			
	70	60	50	40
Fine Digital Manipulation	1	3	6	7
Simple Assembly	1	2	4	6
Gross Body & Power Move.	1	2	2	3

Source: Egstrom (1974)

seriously at 50°F (10°C) and 40°F (4.5°C) temperatures, respectively, as shown in Figure 3-11. Studies also have shown that air consumption can go up by as much as 29 percent when diving in cold water (Dunford and Hayford 1981).

When diving in cold water, it is essential for the diver to:

- Wear thermal protection appropriate for the water temperature (see Figure 5-17)
- Note the first signs of cold hands and feet and loss of dexterity and grip strength
- Note difficulty in performing routine tasks, confusion, or a tendency to repeat tasks or procedures
- Note feelings of being chilled followed by intermittent shivering, even though routine tasks can still be performed
- Terminate a dive if any of the above symptoms are present
- Be aware that even when properly dressed, hypothermia may develop without shivering
- Watch the buddy diver and take heed of any behavioral changes that may indicate existing or approaching hypothermia.

3.4.3 Survival in Cold Water

If ship abandonment is necessary, there are procedures that can significantly increase the chances of survival, even in extremely cold water. Records show that ship sinkings, even in the worst cases, usually require at least 15 to 30 minutes. This affords valuable time for preparation. The following procedures should be carried out (U.S. Coast Guard 1975):

- Locate and don a personal flotation device as quickly as possible.
- Try to enter the water in a lifeboat or raft to avoid wetting insulating clothing and losing body heat.
- Wear several layers of clothing because the trapped air provides insulation. Even in the water, the extra layers of clothing will reduce the rate of body heat loss.
- Especially protect the head, neck, groin, and the sides of the chest, because these are areas of rapid heat loss.
- If it is necessary to enter the water, do so slowly to minimize the likelihood of increasing breathing rate, swallowing water, shock, and death. If jumping is necessary, pinch the nose and hold the breath.
- Once in the water, orient yourself with respect to lifeboats, floating objects, etc. Also button up and turn on signal lights as quickly as possible before manual dexterity is lost.
- Do not attempt to swim except to a nearby craft, fellow survivor, or floating object. Swimming will pump out the warmed water between the body and clothing layers and cause the blood to move from the body core to the extremities, thus increasing body heat loss.
- Keep the head and neck out of the water.
- The best position to conserve body heat is to hold the knees against the chest in a doubled-up fashion with the arms tight around the side of the chest. If others are nearby, huddle together and maintain maximum body contact.
- Board a life raft or floating object as soon as possible.
- Keep a positive attitude, because a will to live does make a difference.

3.4.4 Rewarming

At the end of a dive, a cold diver should be rewarmed. This can be accomplished by having the diver drink hot liquids such as soup or coffee, dry off in a warm place, and bathe in warm water. Studies have shown that rewarming in 104°F (40°C) water reestablishes normal body temperature 67 percent faster than rewarming in 100°F (38°C) air (Strauss and Vaughan 1981). Cold divers should not make a second dive on the same day, because it is difficult to know when body heat has been restored. However, if a second dive is necessary, it is advisable to overdo the rewarming until sweating occurs, which indicates that body heat has been restored. Exercising to generate internal heat is also helpful to speed up the rewarming process. The diver should then change into warm, dry clothing and continue some mild exercise to improve heat production and circulation. Several hours may be required to restore all the body heat lost. Drinking alcohol is not beneficial, because it increases circulation of blood to the skin and speeds the loss of body heat in cold surroundings. A diver who is so hypothermic that he or she is helpless, irrational, or lethargic should be rewarmed more vigorously. Ideally, a hot bath should be used, but if none is available, a hot water suit, electric blanket, or inhalation rewarming are suitable methods. A hypothermic diver who is helpless, irrational, lethargic, or unconscious needs medical attention and immediate and vigorous rewarming, by any of the prescribed techniques (see Section 18.8.3 for further discussion of rewarming).

WARNING

Divers Who Have Been Chilled on Decompression Dives (or Dives Near the Decompression Limit) Should Not Take Very Hot Baths or Showers Because These May Stimulate Bubble Formation

3.5 EFFECTS OF HEAT (HYPERTHERMIA)

Unlike hypothermia, hyperthermia rarely is produced by immersion in water. However, if the water temperature reaches 85°F (29.4°C), there is little or no difference in temperature between the skin and water and heat cannot be transferred to the water. If heavy exercise is performed under such conditions, there can be serious overheating problems (Bove 1984).

Hyperthermia is encountered more commonly during dive preparation where a diver, especially one encased for a long time in a wet suit in the hot sun, can overheat. The symptoms of hyperthermia include heat exhaustion (see Section 18.8.1), with accompanying feelings of dizziness, disorientation, rapid pulse, hyperventilation, and potential loss of consciousness. A more serious result of hyperthermia is heat stroke, which can cause death (see Section 18.1.8). An important factor that increases the risk of hyperthermia is dehydration, which can develop quickly as a result of excessive sweating and lack of fluid replacement. Because it reduces the volume of blood available for circulation to the skin, dehydration increases the chances of divers becoming hyperthermic. Dehydration also increases the likelihood of decompression sickness as a result of inadequate blood flow to the muscles and tissues. Water and juices are recommended for ingestion because alcohol and other fluids act as diuretics, which will only make matters worse. Divers who develop hyperthermia should be put in a cool place, given fluids, and cooled with water poured over the skin until the body temperature returns to normal.

3.6 DRUGS AND DIVING

The use of prescribed or over-the-counter medications while diving is a complex issue. There are no simple answers to questions about which drugs are best for which conditions in a hyperbaric environment. Individual variability, existing medical and physical conditions, and the mental and physical requirements of diving all must be taken into account before pharmacologically active agents are used.

3.6.1 Prescription Drugs

Drug-induced physiological and psychological responses often are altered in a hyperbaric environment. The normal metabolic and excretion patterns of drugs taken at one atmosphere may be significantly and pathologically altered once the diver becomes pressurized. An understanding of the types of changes that occur, the implications of these changes, and the relationships between and among drugs, the environment, and the diver are critical if therapeutic accidents are to be avoided. Specific concerns include the following:

- The manner in which the drug is absorbed, metabolized, and excreted by the body in a hyperbaric environment;
- The physical impact of the type of breathing gas, increased density of the gases, water temperature, and other environmental factors, and the degree of diver exertion all contribute to the total effect of a medication;
- Acceptable side effects, like drowsiness from antihistamines, may be tolerated on the surface. In the hyperbaric environment, however, such side effects may become unacceptable, leading in some cases to serious morbidity or even death. Impairment of cognitive function, neuromuscular strength and coordination, or integration of thought and action can have catastrophic results while diving.

In addition to the antihistamines, drugs commonly used that may adversely affect diver safety and performance include: motion sickness remedies, amphetamines, tranquilizers, sedatives, hypertensive drugs, and decongestants, some of which have been found to induce impaired coordination, cardiovascular effects, addiction, and inflammation of the lower airways. It is noteworthy that the effects of some of these drugs may appear to have worn off on the surface, only to return when the diver becomes pressurized (Anonymous 1986).

While taking medication, therefore, careful consideration should be given to the following elements before diving:

- Why are the drugs being used, and are there underlying medical conditions that may be relatively or absolutely contraindicated for divers (Kindwall 1976)?
- What is the half-life of the drug, and for what period of time before or after its use should the diver not be exposed to a high-pressure environment?
- Will the side effects of the drug increase the associated risks of diving to an unacceptable level?
- Will the drug interfere with physical performance?
- Will the drug impair exercise tolerance?
- Does the drug produce rebound phenomena?

A conscientious diver will discuss these questions with his/her physician before diving while taking prescribed or over-the-counter medications.

3.6.2 Illicit Drugs

It is obvious that cognitive and motor performance can be impaired by the abuse of psychoactive agents. Alcohol and marijuana (and other cannabis products) are the most commonly abused central nervous system depressants in the world today. Research clearly indicates that their use is addictive and in some cases (e.g., with concurrent administration of barbiturates) can potentiate other central nervous system depressants. For example, in addition to being a depressant and having other subjective effects, alcohol can cause reduced blood glucose levels, which can lead in turn to weakness and confusion. Alcohol also causes blood vessel dilation, which can interfere with proper maintenance of body temperature while diving (see Section 3.4). Because of its diuretic action, alcohol can contribute significantly to body dehydration, especially in the tropics, where divers may combine alcohol with the consumption of caffeine-containing drinks such as tea, coffee, and colas.

There are reports that the use of marijuana preceding cold water dives can reduce a diver's cold tolerance and breath-holding capability, cause general discomfort, unexplainable apprehension, and a desire to terminate a dive prematurely (Tzimoulis 1982). It is important to note that the effects of smoking marijuana can last for up to 24 hours (Anonymous 1986).

Cocaine is currently the most commonly abused central nervous system stimulant. Its relatively short action belies the hazard it poses to the diver. The hypermetabolic state that occurs during the use of cocaine (it is rarely used alone and is often used with alcohol or marijuana) may place the diver at risk of subsequent fatigue, mental depression, acidosis, and the inability to respond promptly to life-threatening emergencies. It also increases the likelihood of an oxygen seizure and can disturb the normal rhythm of the heart (Anonymous 1986).

Divers and their physicians have an obligation to communicate with one another. The clinician has the responsibility to explain the nature of his or her treatment to the diver, and the diver has the responsibility of indicating to the treating clinician that a diving exposure is anticipated. In general, divers should be discouraged from using medications before diving. The sharing of medications among divers also should be discouraged. A diving exposure is not a good opportunity for either a clinician or a diver to determine whether a drug will be safe and efficacious for a given individual. Conservative and safe practices are required for the well-being and survival of the diver. Abstinence from diving may be the most conservative approach for an individual requiring systemic medication (Walsh and Ginzburg 1984). (For a comprehensive review of the effects of drugs in a hyperbaric environment, the reader is referred to Walsh 1980.)

SECTION 4
COMPRESSED AIR AND SUPPORT EQUIPMENT

COMPRESSED AIR AND SUPPORT EQUIPMENT

4

4.0 GENERAL

This section describes the composition and characteristics of compressed air, the most commonly used breathing mixture for diving, and the precautions that must be taken when compressed air is used as a breathing medium for divers. It also discusses the equipment used in air diving, including compressors and cylinders, and its maintenance and inspection.

4.1 COMPRESSED AIR

Compressed air is the most frequently used diver's breathing medium. In its natural state at sea level pressure, compressed air consists of nitrogen, oxygen, argon, carbon dioxide, and trace amounts of other gases. Table 4-1 shows the natural composition of air.

Table 4-1
Composition of Air in its Natural State

Gas	Percent by volume
Nitrogen	78.084
Oxygen	20.946
Argon	.934
Carbon dioxide	.033
Rare gases	.033

Source: NOAA (1979)

All ambient air does not meet the standards of purity necessary for use as a diver's breathing medium. For example, in urban areas the carbon monoxide concentration in the air may be high, and in some cases it may reach a concentration of 50-100 parts per million (ppm). Ambient air may also contain dust, sulfur, oxides, and other impurities. These contaminants derive from industrial sources and automotive exhausts and must be avoided in the breathing air supplied to a diver.

Scuba cylinders should not be filled from an ambient air source when an air pollution alert is in effect. The Environmental Protection Agency (EPA) monitors ozone and other oxidants in metropolitan areas, and the local EPA office should be consulted before a diving operation is undertaken in an area suspected of having high pollutant levels. The potential hazard presented by breathing air obtained from ambient sources is underlined by the fact that at least 70 metropolitan areas in the United States were unable to achieve compliance with Federal limits for carbon monoxide by the end of 1987.

In addition to airborne pollutants, the air compressor machinery and storage system themselves may introduce contaminants, including lubricating oil and its vapor, into the breathing medium. Additionally, the temperature of the gas being compressed can be high enough at each successive stage to cause pyrolytic decomposition of any hydrocarbon compounds present. This is particularly true if the compressor's interstage coolers are not functioning properly. Intercooler malfunction can be caused by excessive condensate, impaired cooling water circulation, or, in the case of air radiator coolers, by loss of cooling air flow caused by trash, dirt, or lint getting into the radiator fins.

The free air intake of the compressor must be located to draw air from an area where there are no contaminants. Potential contaminants include engine or ventilation exhaust; fumes or vapors from stored chemicals, fuel, or paint; and excess moisture.

No compressor should be allowed to operate with its intake or first-stage suction blocked, because this will produce a vacuum within the cylinders that can rapidly draw lubricating oil or oil vapor from the compressor crankcase into the air system. Some effective methods of preventing the intake of contaminated air are discussed below.

4.1.1 General Safety Precautions for Compressed Air

There are three primary safety concerns associated with the use of compressed air or any compressed gas. These are:

- That the gas be sufficiently pure and appropriate for its intended use;
- That compressed gas cylinders or storage cylinders be properly labeled and handled;
- That cylinders be protected from fire and other hazards.

Compressed air is available from many sources. Most of it, however, is produced for industrial purposes and is therefore not of the purity necessary for use as a diver's breathing medium. When compressed air is purchased from a manufacturer, it is essential that the gas be certified by the manufacturer to be of high purity, free of oil contaminants, and suitable for breathing. Compressed air suspected of being contaminated should not be used for diving until tested and found safe.

Proper identification and careful handling of compressed gas cylinders are essential to safety. Compressed gas cylinders used to transport gas under pressure are subject to Department of Transportation (DOT) regulations. These regulations include design, material, inspection, and marking requirements (see Section 4.3). Compressed gas cylinders can be extremely hazardous if mishandled and should be stored securely in a rack, preferably in the upright position.

When in transit, cylinders should be secured against rolling. Standing an unsecured cylinder on end or allowing it to roll unsecured could result in the explosive rupture of the cylinder. Cylinders can become deadly projectiles capable of penetrating a wall, and they can propel themselves at great speeds over long distances.

Scuba cylinders are often fitted with a rubber or plastic boot that has holes in it to permit draining. These boots fit over the base of the cylinder and help to keep the cylinder in an upright position. However, cylinders equipped with such boots should not be left unsecured in an upright position, because the boot alone does not provide sufficient protection against falling.

NOTE

Cylinder boots should be removed periodically and the cylinder checked for evidence of corrosion.

Compressed gas cylinders are protected against excessive overpressure by a rupture disk on the valve. Because regulators or gauges may fail when a cylinder valve is opened to check the cylinder pressure, it is important to stand to the side rather than in the line of discharge to avoid the blast effect in case of failure.

WARNING

Do Not Stand in the Line of Discharge When Opening a High-Pressure Cylinder

If a cylinder valve is suspected of having a thread or seal leak, it should be completely discharged before any attempt is made to repair the leak. Leaks can sometimes be detected by painting a 20 percent detergent soap solution (called a snoop) over the external parts of the valve with a brush. Even small leaks will be obvious because they will cause a froth of bubbles to form. After the leak has been repaired, the soap solution used for leak detection must be removed completely with fresh water and the valve dried carefully before reassembly.

Scuba cylinders generally are not color-coded or labeled as to type of gas contained; however, large gas cylinders may be color-coded and labeled. The label should be used to identify the contents of a gas cylinder, because color-coding is not standardized.

WARNING

Because Colors Vary Among Manufacturers, the Content of Large Cylinders Should Always Be Identified By Label—Do Not Rely on Cylinder Color

Several special safety precautions to be observed when using compressed gas are noted on the label of gas cylinders. In general, these precautions concern the flammability of the gas and its ability to support combustion. Although not in itself flammable, compressed air does support combustion and should therefore not be used or stored in an area where open flames, hot work, or flammable gases are present.

4.2 AIR COMPRESSORS AND FILTERING SYSTEMS

Air compressors are the most common source of diver's breathing air. The compressor used for umbilical diving is generally backed up by a bank of high-pressure gas storage cylinders to reduce the possibility of interrupting the diver's breathing gas supply because of loss of power or compressor malfunction.

There are two main types of compressors: high-pressure, low-volume, for use in filling scuba cylinders; and low-pressure, high-volume, used for umbilical diving. A compressor is rated at the pressure at which it will unload or at which the unloading switches will activate. A compressor must have the output volume to provide sufficient breathing medium and to provide pressure above the range equivalent to the ambient pressure the diver will experience at depth. When evaluating compressor capacity, the different overbottom pressure and volume requirements of different types of underwater breathing apparatus and/or helmets must be taken into consideration, as well as umbilical length and diameter.

Any air compressor used for a diver's surface-supplied system must have an accumulator (volume cylinder) as an integral part of the system. The accumulator will provide a limited emergency supply of air if the compressor fails.

As the number of scientific, educational, and sport divers increases, there is a concomitant rise in the number and variety of air compressors being used to supply breathing air. Operators should become thoroughly familiar with the requirements associated with the production of breathing air. To ensure proper maintenance and care, organizations using compressors should assign the responsibility for the operation of compressors to a specific individual.

Air compressors are generally rated by two parameters: the maximum pressure (measured in pounds per square inch gauge, or psig) they can deliver and the output volume (measured in standard cubic feet per minute, or scfm) that can be delivered at that pressure. To be effective, both the output volume and pressure must be equal to or exceed the requirements of the system they supply.

Air compressors commonly used to provide divers' breathing air may be classified in the following groups:

- High-Volume, Low-Pressure Air Compressors. These compressors are most often used to support surface-supplied operations or to supply hyperbaric chambers. They are generally found at sites where large-scale diving operations are being conducted or aboard surface platforms fitted out for diving. Units commonly used have output volumes of between 50 and 200 scfm at maximum discharge pressures of between 150 and 300 psig. These units may be either permanently installed or portable. Portable units are generally built into a skid assembly along with a power source (diesel engine, gasoline engine, or electric motor), volume cylinder, filter assembly, distribution manifold for divers' air, and a rack for storing divers' umbilical assemblies.
- Low-Volume, High-Pressure Air Compressors. These compressors are used for filling scuba cylinders and high-pressure air storage systems that provide support for surface-supplied diving and hyperbaric chambers. Portable units used for filling scuba cylinders are commonly available with a volumetric capacity of 2 to 5 scfm at a discharge pressure adequate to fully charge the cylinders (2250 or 3000 psig, depending on the type of cylinder).

Large, high-pressure cylinders are advantageous to use as a source of breathing gas when there is convenient access to a high-pressure compressor for recharging. Using cylinders as the gas source reduces the chance of losing the primary supply, since the entire volume of gas needed for a dive is compressed and stored before the dive. Most lockout submersibles carry the diver's gas supply in high-pressure cylinders incorporated into the system. Compressed gas cylinders are also generally mounted on the exteriors of underwater habitats, submersibles, and diving bells to provide a backup gas supply in case of emergency, and divers using the habitat as a base can refill their scuba cylinders from these mounted cylinders.

Many types of compressors are available: centrifugal, rotary screw, axial flow, and reciprocating. The most commonly used type in the diving industry is the reciprocating, or piston-in-cylinder, type. These compressors are further classified as "oil-lubricated" or "non-oil-lubricated," depending on whether or not they require lubrication of their compression cylinders.

In an oil-lubricated compressor, the oil in the crankcase assembly also lubricates the pistons and cylinder walls. As a result, some of the oil may come into direct contact with the air being compressed. The lubricants used in machines that provide breathing air must be of the quality specified for breathing air and be so designated by the equipment manufacturer. One lubricant should not be substituted for another unless the manufacturer's directions so specify. Chlorinated lubricants, synthetics, or phosphate esters (either pure or in a mixture) should never be used. Oil-free compressors usually employ a standard oil-lubricated crankcase assembly similar to that of oil-lubricated machines; however, the pumping chambers in oil-free machines are designed to run either with water lubrication or with no lubrication at all. For this reason, some manufacturers describe their machines as oil-free, even though the breakdown of such compressors could still result in oily breathing air. The mechanical connections between the pumping chambers and the crankcase on oil-free machines are carefully designed to prevent the migration of crankcase oil into the pumping chambers. The all-purpose crankcase lubricant recommended by the manufacturer can usually be used for oil-free compressors. The compressors used to provide breathing air in hospitals are of the oil-free type, but these machines are still not widely used in operational diving.

The production of compressed air is a complex process. The process begins as the piston in the first/second stage head strokes upward in its cylinder. At that point, the intake valve to the first stage closes and the intake valve to the second stage opens. At the point of maximum compression, the exit valve from the first stage opens and compressed air is admitted to the first-stage intercooler. Intercoolers cool the air before further recompression and cause water and oil vapors to condense and collect as the air passes through the air/liquid separator at the discharge end of the intercooler. The separator is fitted with a drain valve that must be opened periodically to drain off accumulated liquids. Each intercooler assembly is also fitted with a relief valve that opens if the pressure rises above a safe level.

The second stage of compression takes place on the downstroke of the piston, during which the second-stage inlet valve closes and the air is further compressed. At the moment of maximum compression, the exit valve to the second stage opens and compressed air is admitted to the second-stage intercooler.

In a typical three-stage compressor, the air is taken from ambient pressure to approximately 2250 psi. Compressors typically use a ratio of 6:1, although this may vary with different makes and models of compressors. Each succeeding cylinder is proportionately smaller in volume than the previous one. Some efficiency (approximately 10 percent) is lost because of the volume of the intercoolers and residual cylinder volumes; this factor is called volumetric efficiency.

Air leaving a compressor must be cooled and passed through an air/liquid separator to remove any condensed water and oil vapors before storage or immediate use. Air from an oil-free compressor does not generally require any further treatment unless the application requires that it be further dried or there is concern about possible contamination of the intake air. Air from an oil-lubricated compressor must be carefully filtered to remove any possible oil mist, oil vapors, possible byproducts from oil oxidation in the compressor (predominantly carbon monoxide), or odors. Several types of filtration systems are available. To use most filtration agents properly, it is necessary to place them in the filtration system in a specific order. To do this, the direction of the air flow through the filter system must be known, and, if there is any doubt, it should be checked. Like other high-pressure components, filter canisters should be inspected visually for corrosion damage (High 1987). An inspection protocol can be helpful when performing filter canister inspections.

For purposes of dehydration and adsorption, substances known as molecular sieves are often used. A molecular sieve is a material having an extremely large surface area to enhance its capacity for adsorption. Since it removes harmful contaminants by causing them to adhere to its surface, the sieve itself remains inert and virtually unchanged physically during the purification process. With appropriate periodic regeneration processes, most molecular sieves are capable of removing a wide range of contaminants, including nitrogen dioxide and most odors. However, the most effective way to remove hydrocarbons and odors is still with the use of activated carbon, which acts much like a molecular sieve.

Another popular filtration system involves the following components, which are used in the sequence shown:

- coalescing section to remove oil mist;
- dessicant section to remove water vapor, nitrogen dioxide, hydrocarbons, and other contaminants removable by adsorption;
- activated charcoal section for removal of residual odors and tastes; and
- Hopcalite® section for carbon monoxide removal.

The Hopcalite® oxidizes the carbon monoxide to carbon dioxide. Hopcalite® is a true catalyst in this reaction and is neither consumed nor exhausted in the process. The amount of carbon dioxide produced by the catalytic action is so small as to be physiologically insignificant. The amount of oxygen used up is approximately 0.5 part of oxygen per million parts of carbon monoxide, which has no appreciable effect on the air produced. The lifetime of this system is usually determined by the lifetime of the dessicant, since Hopcalite® is quickly "poisoned" and rendered ineffective by excessive water vapor. An aspect of this process that is not widely understood is that the carbon monoxide oxidation process releases substantial quantities of heat. If a Hopcalite® filter becomes extremely hot or shows signs of discoloration, the compressor output air should be checked for elevated carbon monoxide levels.

In addition to Hopcalite®, the use of activated alumina in combination with Multi-sorb® is also widespread. No matter what technique is employed, the location of the compressor intake with respect to possible sources of contamination is an important factor in ensuring satisfactory air quality. Compressors should not be operated near the exhausts of internal combustion engines, sewer manholes, sandblasting or painting operations, electric arcs, or sources of smoke. Plastic containers of volatile liquids can give off fumes even when they are tightly closed. Intakes must be provided with filters for removing dust and other particles. Proper orientation to wind direction is also critical in setting up air compressor systems.

The final step in the production of pure air is the filling station, usually located in a dive shop, on board ship, or near a diving installation. It is important for the diver to inspect the filling station to ensure that proper safety precautions are being observed and that Federal, state, and local regulations are being followed. Figure 4-1 is a schematic of the processing of air from the intake to the scuba cylinder. (Note that the system depicted in Figure 4-1 includes a high-pressure booster pump, which can increase the efficiency of cylinder filling operations by providing air at the filling station at a pressure above that of the air storage cylinder.)

For some diving operations, air is supplied by the manufacturer in banks of high-pressure cylinders. These cylinder banks are fitted with valves and manifolds and may be used to provide breathing air in surface-supplied diving operations and for filling scuba cylinders.

4.2.1 Maintenance

Both the compressor and filter system must be maintained properly. When running, the compressor must be cooled adequately, because the primary factor causing the breakdown of lubricants and contamination of the compressed air is high temperature in the compressor cylinder. Cylinder heads may be cooled by air blowers or water spray systems or by cooling systems integral to the compressor machinery. A cylinder head temperature controller is valuable in eliminating the possibility of excessive cylinder temperatures. Particular attention should be paid to draining the interstage and final-stage separators. Compressors and filters are usually given routine maintenance on an hours-of-operation basis. Filters should be examined and replaced in accordance with the manufacturer's specifications. The compressor lubricant and mechanical parts should be replaced on a rigorous schedule, based on the manufacturer's recommendations or the results of an air analysis. Analysis of the output air from oil-lubricated compressor systems should be performed on a periodic basis. Oil mist analyses are difficult to perform and require careful collection techniques as well as qualified laboratory analysis of the samples. However, carbon monoxide analyses, by far the most important, can easily be performed in the field using colorimetric tubes. (See Section 15.4 for information on contaminant analysis.)

A log should be kept for each compressor. The log should record all time in service, maintenance, and air analysis information.

4.2.2 Lubricants

Oil-lubricated compressors always have a small amount of oil on the interior of the cylinder's walls, and some of this oil mixes with the air being compressed. This oil is filtered out by the compressor's filtering system. Because an improperly functioning filter can raise temperatures sufficiently to decompose or ignite the oil, it is important to select oil to be used as a lubricant carefully.

The oil's flashpoint (the temperature of the liquid oil at which sufficient vapors are given off to produce a flash when a flame is applied) and auto-ignition point (the temperature at which the oil, when mixed with air, will burn without an ignition source) are both important considerations. The most desirable compressor lubricants have higher-than-average flashpoints and low volatility. The oils recommended by the manufacturer of the compressor are generally the safest and most efficient lubricants for this equipment.

4.3 COMPRESSED GAS CYLINDERS

The scuba cylinder or cylinders are secured to the diver's back by an adjustable harness or form-fitting backpack assembly equipped with a clamping mechanism. Regardless of which model is employed, all straps securing the apparatus should be equipped with corrosion-resistant, quick-release buckles to permit rapid opening under emergency conditions.

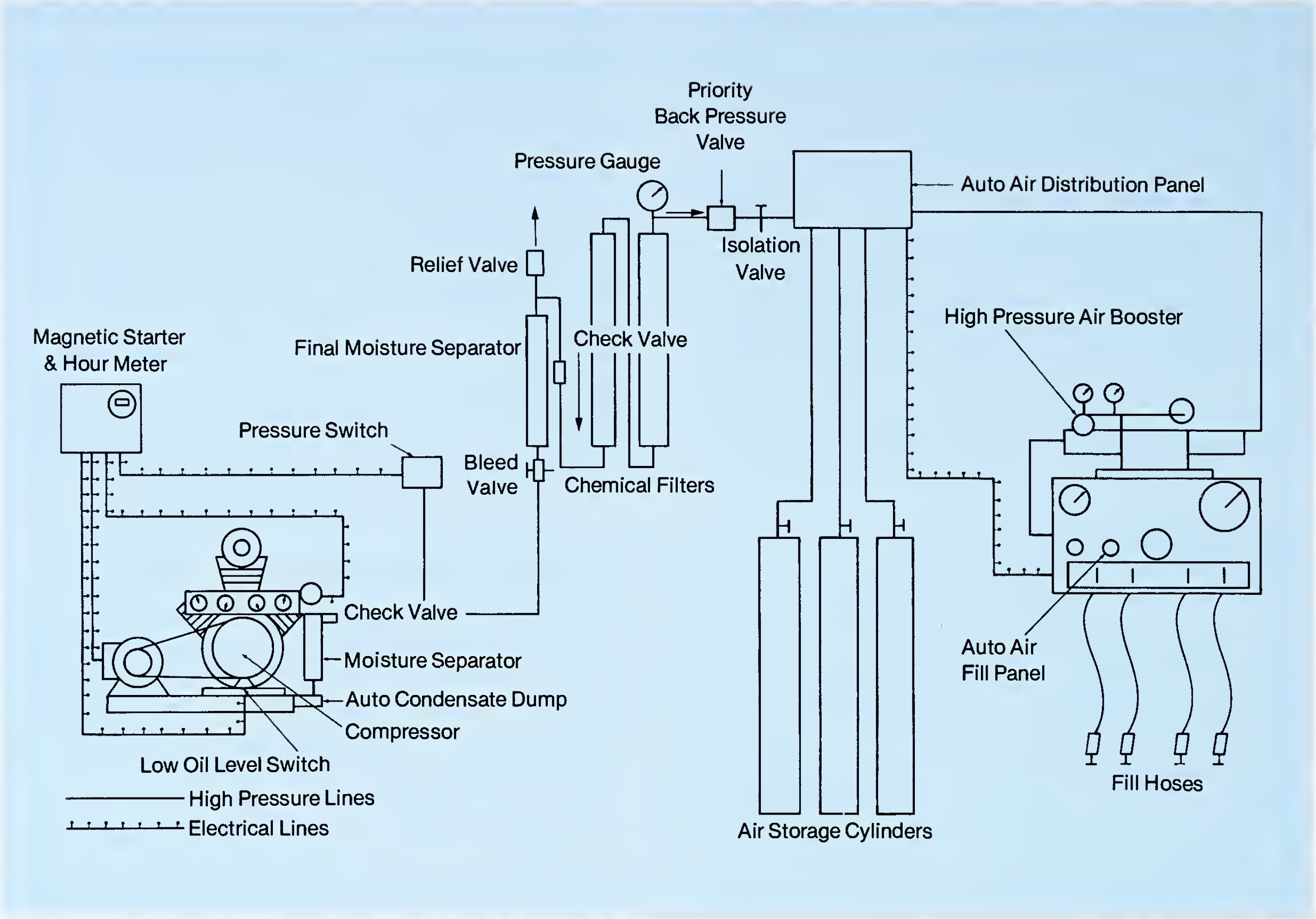
Scuba cylinders contain the compressed breathing gas (usually air) to be used by a diver. Most cylinders for diving are of steel or aluminum alloy construction, specially designed and manufactured to contain compressed air safely at service pressures from 2250 to 3000 psig (158 to 211 kg/cm^2) or greater.

4.3.1 Cylinder Markings

Regardless of cylinder type, data describing the cylinder must be clearly stamped into the shoulder of the cylinder, which must be manufactured in accordance with the precise specifications provided by the Interstate Commerce Commission (ICC) (until 1970), thereafter by the DOT, and most recently reflected on cylinders as CTC/DOT, which indicates equivalency with requirements of the Canadian Transport Commission (High 1986a).

Regulatory changes in the more than 35 years since scuba cylinders entered service in the United States have produced a variety of code markings. Typically, steel cylinders carry the code *DOT* (or ICC), *3AA* (steel type), and a *service pressure* of 2250 psig (158 kg/cm^2) or higher on the first line. These marks are followed by the *serial number, cylinder manufacturer's symbol* (before 1982, the symbol of the user or equipment distributor), the original *hydrostatic test*

Figure 4-1
Production of Diver's Breathing Air



Courtesy Skin Diver Magazine

date with testor's symbol, and a *plus* (+) *mark,* which indicates that a 10 percent fill over-service-pressure is allowed for the 5-year period of the original hydrostatic test.

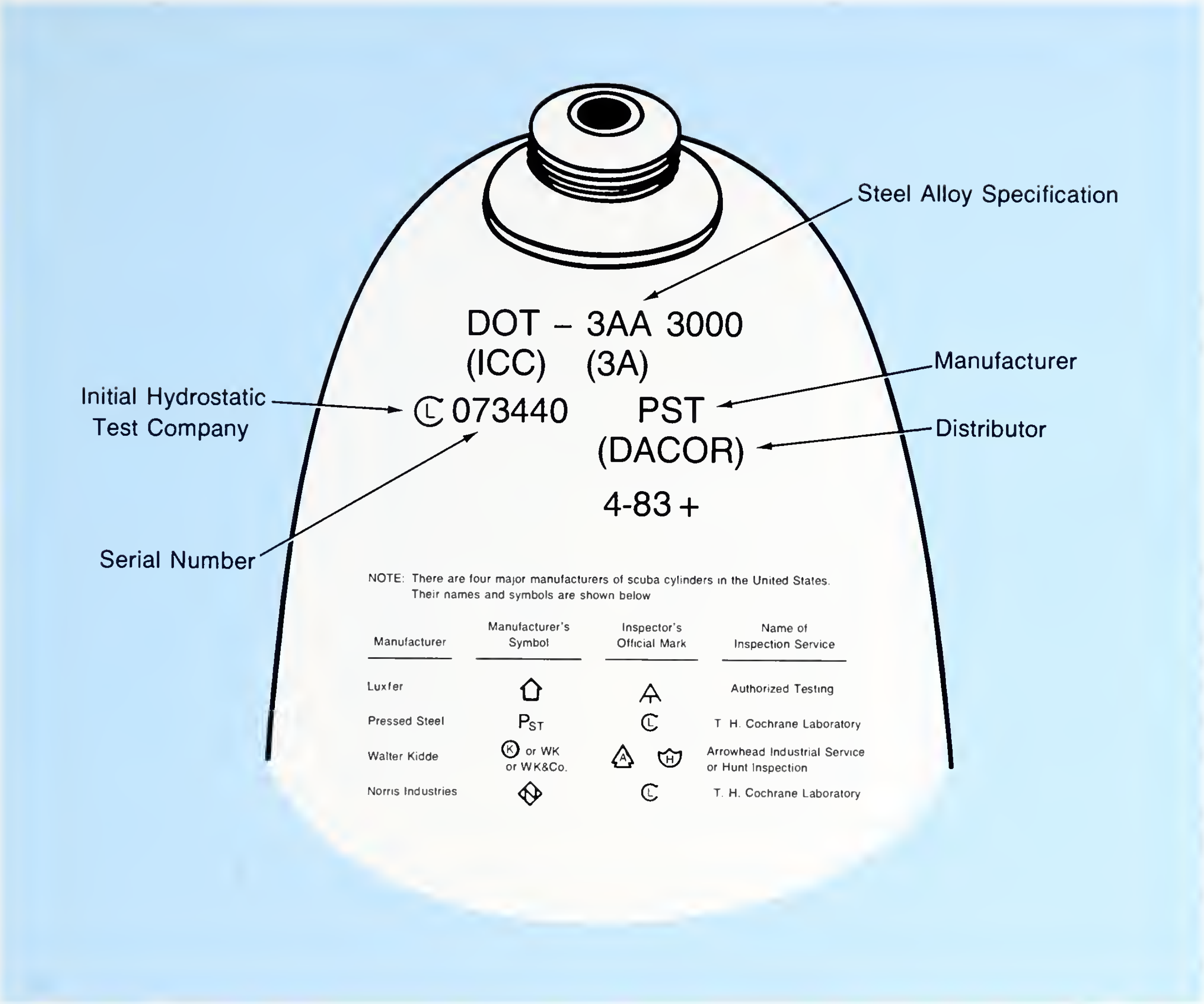
Additional hydrostatic test dates, with the testors' codes, will be added on successful retest at required 5-year or shorter intervals. However, since hydrostatic test facilities rarely retest scuba cylinders appropriately to permit inclusion of the plus mark (+) for continued 10 percent overfill, few steel cylinders are filled in excess of the designated service pressure after the initial period. (Figure 4-2 shows steel scuba cylinder markings.) Current practice allows a cylinder submitted for the plus (+), that is the 10 percent overfill, to fail the elastic expansion test and to be reevaluated at the lower service pressure on the basis of the permanent expansion test (High 1986b).

Aluminum alloy scuba cylinders entered U.S. commercial service in 1971 and are code-marked in a somewhat different manner than steel cylinders. Initially, DOT issued special permits or exemptions for the manufacture of aluminum cylinders. These are indicated in some code markings as SP6498 or E6498, followed by the service pressure, which typically ranges from 2475 to 3000 psi (174 to 211 kg/cm^2). No plus (+) or overfill allowance is used with aluminum alloy cylinders. Currently, aluminum cylinders reflect DOT and CTC equivalency, a new material designation (3AL), the service pressure, and a mark indicating volume and that the cylinder is intended for scuba service (S80), as shown in Figure 4-3.

NOTE

Aluminum alloy cylinders should never be filled in excess of marked service pressure, and steel cylinders without a plus (+) after the current hydrostatic test date should also not be filled over their marked service pressures.

Figure 4-2
Steel Cylinder Markings



NOTE: There are four major manufacturers of scuba cylinders in the United States. Their names and symbols are shown below

Manufacturer	Manufacturer's Symbol	Inspector's Official Mark	Name of Inspection Service
Luxfer	⌂	A	Authorized Testing
Pressed Steel	P_{ST}	Ⓛ	T H. Cochrane Laboratory
Walter Kidde	Ⓚ or WK or WK&Co.	Ⓐ Ⓗ	Arrowhead Industrial Service or Hunt Inspection
Norris Industries	◈	Ⓛ	T. H. Cochrane Laboratory

Derived from NOAA (1979)

The internal volume of a cylinder is a function of its physical dimensions and may be expressed in cubic inches or cubic feet. Of more interest is the capacity of the cylinder, which is the quantity of gas at surface pressure that can be compressed into the cylinder at its rated pressure. The capacity usually is expressed in standard cubic feet or standard liters of gas. Cylinders of various capacities are commercially available. Steel scuba cylinders generally have a rated working pressure of 2250 psig (158 kg/cm^2, or 153 atm) and contain 64.7 standard cubic feet (1848 standard liters) of gas. Cylinders with capacities from 26 standard cubic feet (742 standard liters) to over 100 standard cubic feet (2857 standard liters) are used for scuba diving.

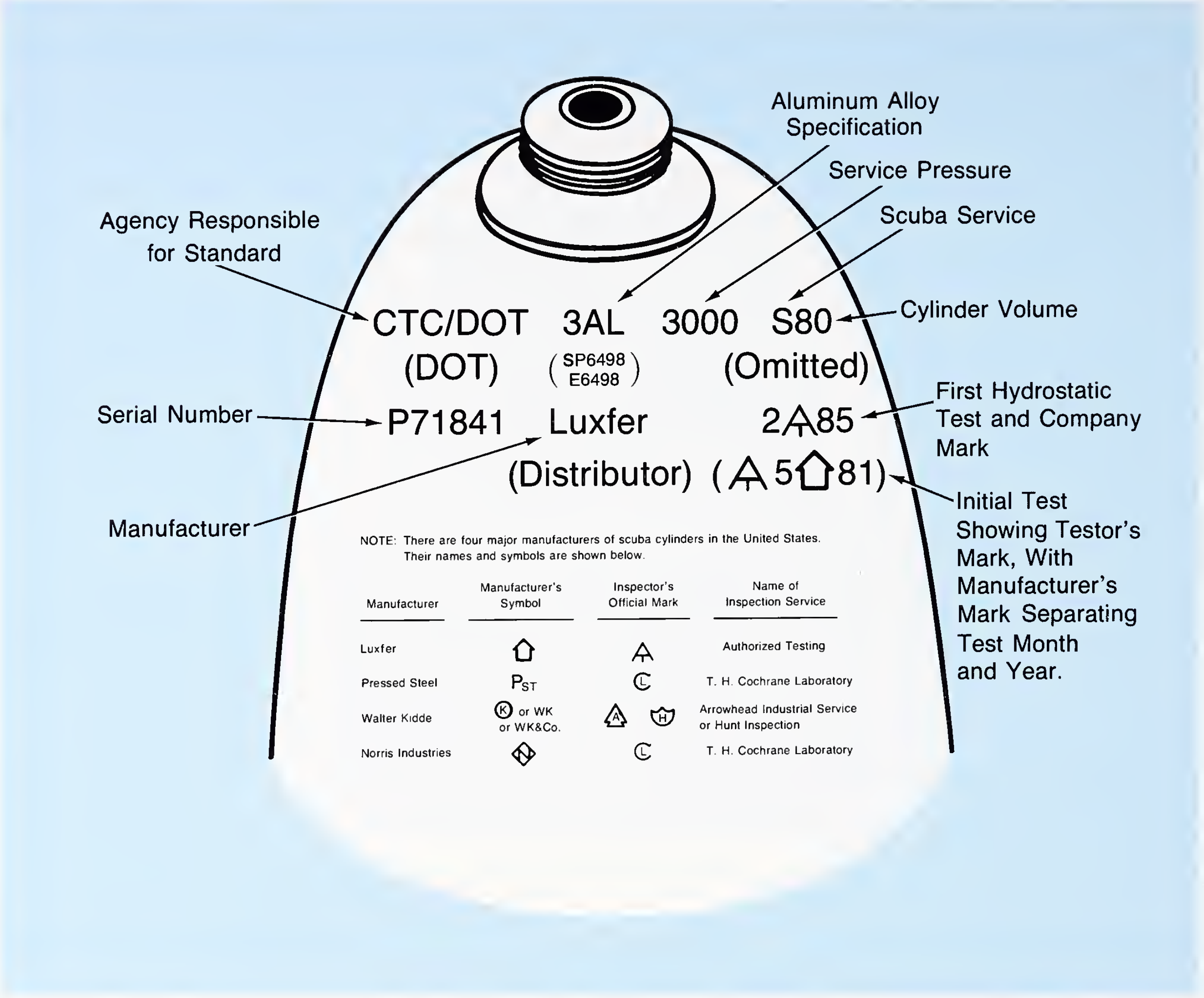
WARNING

Do Not Fill Cylinders Beyond Their Service Pressure

4.3.2 Cylinder Inspection and Maintenance

The exteriors of most steel cylinders are protected against corrosion by galvanized metal (zinc), epoxy paint, or vinyl-plastic coating. The zinc bonds to the cylinder and protects it from air and water. Galvanized exteriors are recommended for protection against corrosion; however, epoxy paint or plastic is unsatisfactory for use over bare steel cylinders, because even

Figure 4-3
Aluminum Cylinder Markings



NOTE: There are four major manufacturers of scuba cylinders in the United States. Their names and symbols are shown below.

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Walter Kidde	Ⓚ or WK or WK&Co.	Ⓐ Ⓗ	Arrowhead Industrial Service or Hunt Inspection
Norris Industries	◈	Ⓛ	T. H. Cochrane Laboratory

Courtesy William L. High

minor abrasions may penetrate these two coatings and expose the underlying metal, allowing oxidation (rusting) to begin immediately. Epoxy paint or plastic is acceptable, however, over zinc-galvanized surfaces because it reduces electrolytic corrosion of the zinc by salt water and imparts an attractive appearance. With proper preventive maintenance, electrolytic corrosion is relatively insignificant on bare zinc coating.

Since internal rusting is a problem, manufacturers formerly applied protective linings on the interiors of cylinders. The use of internal coatings has only been relatively successful, because even a small flaw in the lining allows moisture in the cylinder to penetrate to bare metal. Corrosion under the lining cannot be seen or assessed. Also, the lining tended to loosen and, in some cases, the resulting flakes clogged the valve or the regulator. Damaged linings must be removed.

A corrosion-inhibiting epoxy-polyester finish usually is applied to the exterior of aluminum cylinders both to protect them and to give them an attractive color. If this coating scrapes off, an oxide layer forms that tends to protect the cylinder from further corrosion. Often the interiors of aluminum cylinders have a protective layer over the base metal, such as Alrock® or Irridite®, which is applied during the fabrication process.

Air cylinders and high-pressure manifolds should be rinsed thoroughly with fresh water after each use to remove traces of salt and other deposits. The exterior of the cylinder should be visually inspected for abrasion, dents, and corrosion. If the cylinder has deep abrasions or dents, it should be tested hydrostatically before refilling; external corrosion should be removed and a protective coating applied to prevent further deterioration of the cylinder wall. Care also must be taken to prevent moisture accumulation inside high-pressure cylinders. When a cylinder is completely drained of air while being used with a single-hose regulator, water may enter the cylinder through the regulator if the purge button is depressed, allowing the second-stage valve to open. Cylinders used under water as a source of air for power tools or for lift bags often become contaminated by moisture returning through the valve. Cylinders should be stored with about 100 psi of air remaining in the cylinder to keep water from entering the cylinder.

Cylinders should never be submerged completely before the filler assembly is attached, because small amounts of water may be trapped in the valve orifice and injected into the cylinder. Moisture in a cylinder often can be detected by (1) the presence of a whitish mist when the valve is opened; (2) the sound of sloshing water when the cylinder is tipped back and forth; or (3) a damp or metallic odor to the air in the cylinder. Water in a cylinder can create a particularly dangerous condition in cold water diving, because ice can form in the first stage or in the hose prior to the second-stage valve, causing the flow of air to the diver to be interrupted.

Both steel and aluminum cylinders should be inspected internally by a trained technician at least once a year for damage and corrosion. Cylinders should be inspected more frequently, and perhaps as often as every 3 months, if they are used in a tropical climate or aboard ship, or if they receive especially hard service. A special rod-type low-voltage light that illuminates the entire inside of the cylinder should be used for internal visual inspection. Standards and procedures for the visual inspection of compressed gas cylinders are discussed in detail in High (1987).

Two forms of inspection are used, depending on the interval since the previous inspection or the nature of the suspected problem. An *informal inspection* is a cursory look at a scuba cylinder's exterior and interior to determine if there is a reason to examine it further. A *formal inspection* is a complete evaluation against standards, in which a judgment is reached and evidence of the inspection is affixed to the cylinder in the form of a sticker that attests to the cylinder's suitability for continued use. The sticker should indicate the standard used, the date of inspection, and the facility conducting the inspection.

The visual cylinder inspection procedure is neither complex nor time consuming, but it should be performed only by persons properly trained and using appropriate tools. In general, the cylinder exterior should be compared to standards for:

(1) cuts, gouges, corrosion (general, pitting, line), and stress lines;
(2) dents or bulges;
(3) signs of heat damage;
(4) general abuse;
(5) condition of plating; and
(6) current hydrostatic test date.

Interior cylinder evaluations to standards should assess:

(1) type and amount of cylinder contents (if any);
(2) magnitude of general, pit, or line corrosion;
(3) thread integrity;
(4) defects in interior coating (if any);
(5) sign(s) of substantial material removal;
(6) presence of manufacturer's re-call items (if any); and
(7) internal neck cracks.

There are several methods of hydrostatic testing of cylinders, including direct expansion, pressure recession, and the water jacket method. The most common method is the water jacket method, which involves filling the cylinder with water, placing it in a water-filled pressure chamber, raising the pressure inside the cylinder with a hydraulic pump, and measuring the amount of cylinder expansion in terms of water column displacement. The pressure is increased to five-thirds the rated pressure of the cylinder. According to DOT regulations, a permanent expansion of 10 percent or more of the total expansion indicates that the cylinder is unsafe for use and should be condemned.

Scuba cylinders may be stored at full pressure for short periods of time. However, it has been traditional to store cylinders over longer periods with low pressure to ensure that the valve is not inadvertently opened. There is a potential for moist ambient air to pass through the open valve into the cylinder as air temperatures change. If there is moisture in the cylinder, air at the higher pressure (higher partial pressure of oxygen) accelerates corrosion.

However, a greater danger exists when partially filled aluminum cylinders are exposed to heat, as might occur during a building fire. The metal can soften before the temperature-raised pressure reaches that necessary to burst the frangible safety disk. An explosion may occur well below the cylinder service pressure.

Rules for the use of scuba cylinders are:

(1) Do not fill high-pressure cylinders if the date of the last hydrostatic test has expired (5 years for steel and aluminum cylinders) or if more than 1 year has passed since the last formal visual inspection.
(2) Charge cylinder at a slow rate to prevent excessive heat buildup.
(3) Never exceed the maximum allowable pressure for any particular cylinder.
(4) Never perform maintenance or repairs on a cylinder valve while the cylinder is charged.
(5) Handle charged cylinders carefully. Handling by the valve or body is preferred. Handling by straps or backpack may allow the cylinder to slip or drop.
(6) Store charged cylinders in an upright position in a cool, shady place to prevent overheating.
(7) Secure cylinders properly to prevent falling or rolling.
(8) Internal inspections, hydrostatic tests, and repair work should be performed only by those formally trained to do so.
(9) Have cylinders visually inspected for interior deterioration annually (or more frequently, depending on use).
(10) Inspect cylinders externally before and after each dive for signs of general pitting or line corrosion, dents, cracks, or other damage. Never use a welded, fire-damaged, uninspected, gouged, or scarred cylinder.
(11) Remove cylinder boot periodically to inspect for corrosion and rusting. Boots that inhibit rapid draining and drying should not be used because they allow water to remain in contact with the cylinder, forming corrosion.
(12) Do not completely drain the cylinder of air during dives. This prevents moisture from entering the cylinder.

WARNING

Aluminum Cylinders Should Not Be Heated Above 350°F (177°C) Because This Reduces the Strength of the Cylinder and Could Cause Rupture

4.3.3 Cylinder Valve and Manifold Assembly

Open-circuit scuba cylinders are normally worn on a diver's back with the manifold/valve assembly up. In this configuration, the demand valve of the double-hose regulator rides at the back of the diver's neck. The demand valve of the single-hose regulator is positioned at the diver's mouth, regardless of cylinder orientation. The demand valves of both types must be kept in close proximity to the diver's lungs to ensure a minimum hydrostatic pressure differential between demand valve and respiratory organs, regardless of diver orientation. If this is not achieved, the diver's respiratory system must work harder than necessary to overcome this differential during inhalation (or exhalation, depending on orientation). Thus, the position of the cylinders on the diver's back is especially important when a double-hose regulator is employed.

If diver's air is to be supplied by two or more cylinders simultaneously, a manifold assembly is employed to join the cylinders and provide a common outlet. The manifold consists of sections of high-pressure piping and appropriate fittings specially configured and threaded to incorporate two or more cylinders, a valve, and frangible burst disks into a single functional unit. In addition, it may also contain a reserve valve.

The cylinder valve assembly is a simple, manually operated, multiple-turn valve that controls the flow of high-pressure gas from the scuba cylinder. It also is the point of attachment for the demand regulator. After the regulator has been clamped to the cylinder valve and just before using the apparatus, the valve is opened fully and then backed off one-fourth of a turn. It remains open throughout the dive. On completion of the dive, the cylinder valve is closed and should be bled to atmospheric pressure, which prevents the O-ring from blowing out while the regulator is removed.

When a single cylinder supplies diver's air, the cylinder valve unit is generally sealed directly into the neck of the cylinder by a straight-threaded male connection containing a neoprene O-ring on the valve body. Most cylinders placed in service before 1960 were fitted with a valve having a 0.5-inch tapered thread without O-rings. When a single cylinder is utilized, the cylinder valve assembly houses a high-pressure burst disk as a safety feature to prevent cylinder pressure from reaching a critical level during charging or under conditions of elevated temperature. Old-style lead-filled blowout plugs must be replaced with modern frangible disk assemblies. When a pair of cylinders is employed, two burst disks are installed in the manifold assembly. Valve manufacturers use burst disks designed to rupture at between 125 and 166 percent of the cylinder service pressure. The rating may be stamped on the face of the burst disk assembly to prevent confusion, and disks of different pressure ratings must not be used interchangeably. Valves are not interchangeable between cylinders having different service pressures unless their respective burst disk assemblies are also interchanged.

NOTE

The standard cylinder valve assembly described above is known as a K-valve. A cylinder valve that incorporates a low-air warning/reserve air mechanism is known as a J-valve.

4.3.4 Low-Pressure Air Warning/Reserve Air Mechanism

Several mechanisms are used in open-circuit scuba to perform the important function of warning divers that the air supply is approaching a critically low level. Some of these devices also provide a reserve air supply that allows the diver to proceed safely to the surface. Such a device is generally one of the following: J-valve, submersible cylinder pressure gauge, or auditory warning device. These mechanisms may be incorporated into the cylinder valve/manifold assembly or into the demand regulator. These devices and their limitations are discussed in the following paragraphs.

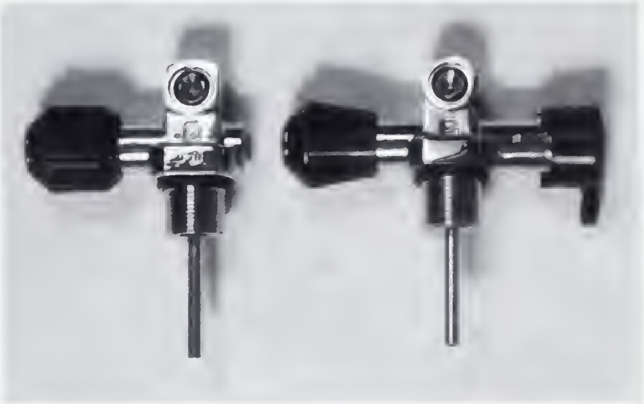
Reserve Valve

The reserve valve (also called a J-valve), illustrated in Figure 4-4, is a spring-loaded check valve that begins to close as the cylinder pressure approaches a predetermined level, generally 300 or 500 psi (23 or 30 kg/cm^2). Until this pressure is approached, the reserve valve permits an unrestricted flow of air to the regulator throughout the dive. At the predetermined pressure, a spring forces a flow check against the port orifice and restricts the air flow, causing increased breathing resistance. This is followed by total obstruction of air flow if the reserve air is not manually released. The remaining or reserve air can be released by manually overriding the spring-loaded check valve.

NOTE

The reserve valve lever must be in the down position when charging cylinders.

Figure 4-4
Valve Assemblies



A. Cylinder Valve B. Reserve Valve

Source: NOAA (1979)

When a diver depresses the cylinder valve/manifold-mounted reserve lever, a plunger pin within the reserve valve advances, forcing the flow check to back off the orifice against the action of the spring. The remaining 300 or 500 psi (23 or 30 kg/cm^2) of air is then made available to the diver.

Divers should be aware that the availability and duration of the reserve air supplied through a reserve valve are dependent on the number of cylinders carried as well as the depth of the dive. The 300 psi (23 kg/cm^2) reserve available is at actual cylinder pressure; it is not 300 psi above ambient pressure. Thus, at a depth of 100 feet (ambient pressure of approximately 50 psi), only 250 psi (17 kg/cm^2) is available until the diver starts to ascend. Also, the reserve valve mechanism retains a reserve air supply only in one cylinder of a twin set of cylinders; the other cylinder or cylinders are at a lower pressure when the reserve valve trips. When the reserve mechanism is activated, the reserve air distributes itself proportionately in all cylinders. For this reason, the reserve valve mechanism employed with twin cylinders must be set to provide a 500-psi reserve. Unfortunately, though generally reliable, the reserve valve mechanism is subject to physical damage or mechanical failure and, if moved as little as 1/8" to 1/4", may be tripped inadvertently early in the dive, which allows the reserve air to be exhausted without the diver's knowledge.

NOTE

Reserve valves should be inspected annually for defects or whenever a malfunction is suspected.

4.3.5 Submersible Cylinder Pressure Gauge

Use of a submersible cylinder pressure gauge (Figure 4-5) is a requirement in nearly all recreational and scientific diving. These gauges have largely replaced constant reserve valves and audio systems. When reading

Figure 4-5
Gauges

Courtesy William L. High

a gauge is difficult, as is the case in low-visibility conditions, a constant reserve valve can be carried as well. In addition, dial faces that glow in the dark increase gauge readability under marginal light conditions. Some newer gauges are able to provide data on the amount of time remaining for the dive at the current breathing gas consumption rate. This feature calculates the pressure drop in the cylinder over time and predicts the amount of air time remaining, assuming a continued constant rate of use. However, divers should be aware that changing their respiration rates can dramatically alter the amount of time remaining at low cylinder pressures.

The use of consoles that allow other types of gauges to be added to the submersible pressure gauge has increased the amount of information that can be obtained when a diver monitors the submersible cylinder pressure gauge. Maximum depth indicators, bottom timers, and compasses are now commonly associated with pressure gauges. However, this use of console gauge holders has added considerably to the mass of the high-pressure hose end, and the hose and gauge must be positioned carefully as a result; the high-pressure hose can be run inside the waist strap on the back pack so that the gauges are located on the thigh in a readable position. When worn improperly, a submersible pressure gauge positioned at the end of a 2- to 3-foot (0.7 to 1 m) length of high-pressure hose can increase the chance that a diver will foul on bottom debris or become entangled with equipment. The gauge supply hose must be connected to a high-pressure port with compatible threads or be used with an adapter.

The high-pressure hose normally has brass fittings with a restricting orifice. Should the high-pressure hose rupture, this orifice prevents rapid loss of cylinder air and allows the diver time to abort the dive and surface. Care must be taken to keep water from getting into the first stage of the regulator before the cylinder valve is opened, because otherwise water could be blown into the submersible pressure gauge and other regulator parts. Divers also should never submerge their scuba cylinders when the valve is off and there is no pressure in the attached regulator.

Gauge readings that err by as much as 300 psi (23 kg/cm^2) or more may occur because gauge accuracy declines with use, especially if small amounts of water have entered the mechanism. Divers should therefore compare their gauges to known cylinder pressures regularly; gauges should be checked at various pressures. Professional dive facilities often use gauges in their high-pressure air systems that are accurate to 1 or 2 percent so they can make cylinders with known pressures available to their customers for comparison. At all NOAA diving units, pressure gauge testing devices are available that can be used for gauge calibration and to assess erratic needle movement.

WARNING

Do Not Look Directly At the Face of Any Pressure Gauge When Turning on the Cylinder Because of the Possibility of Blowout

Because the accuracy of the slow indicator needle declines during normal use, the needle on a defective unit might stick, which could cause the pressure reading to be higher than it actually is. Divers in the field can assess the adequacy of submersible gauge needle function by releasing pressure from the gauge over a 3-minute period while they observe the needle for erratic movement. Defective gauges must be returned to the manufacturer for replacement of parts.

SECTION 5
DIVER AND DIVING EQUIPMENT

DIVER AND DIVING EQUIPMENT

5

5.0 GENERAL

This section describes diving equipment that has proven to be reliable in a wide variety of underwater environments. New models and new types of diving equipment come on the market regularly, and divers should be careful when selecting equipment to ensure that the equipment they have chosen is both safe and efficient. Diving equipment must be maintained properly to perform at its best; selection and maintenance are fundamental to safe, effective diving.

5.1 OPEN-CIRCUIT SCUBA

Self-contained underwater breathing apparatus (scuba) was developed to allow the diver freedom of movement under water. In this diving mode, divers carry their breathing medium on their backs, which allows dives to be conducted without surface support.

A typical open-circuit scuba system consists of a compressed air cylinder (tank) that contains high-pressure air, a regulator that reduces the pressure of the air in the tank to a pressure equal to that of the diver's environment (ambient pressure), and a means of attaching the tank and regulator to the diver. A standard open-circuit scuba system is shown in Figure 5-1.

Three major categories of scuba are currently in use:

- Open-circuit demand;
- Semi-closed-circuit (for mixed gas applications); and
- Closed-circuit.

To select equipment that is appropriate for a particular dive, divers must know and understand the difference between self-contained diving (open-circuit air) and surface-supplied diving.

The advantages of open-circuit scuba are:

- It permits diver mobility;
- The equipment needed can be carried or transported easily;
- It can be conducted from small boats (i.e., this mode requires little support equipment); and
- Training for this mode is widely available.

The disadvantages of open-circuit scuba are that it:

- Cannot be used at great depths;
- Cannot supply breathing gas for dives of long durations;
- Does not permit communication between the diver and the surface;
- Cannot be used under conditions of poor visibility;
- Cannot be used for cold-water diving; and
- Requires a minimum of two divers (i.e., use of the buddy system) for safety.

Figure 5-1
Open-Circuit Scuba Equipment

Courtesy U.S. Divers

5.1.1 Demand Regulators

Demand regulators are used to reduce the pressure of the breathing gas coming from high-pressure cylinders to ambient pressure and to provide gas to a diver on demand; the pressure differential created by the respiratory action of the diver's lungs is the signal to the regulator to provide gas to the diver. Most regulators automatically adjust to changes in the diver's depth or respiration rate and conserve the gas supply by delivering only the quantity of breathing gas required. The function of "upstream" and "downstream" valves is critical to the operation of regulators. An upstream valve is one that opens against the air flow coming from the high-pressure gas in the cylinder. Because this valve is forced closed by gas of higher pressure, it increases breathing resistance. If a major regulator malfunction occurs, the upstream valve is closed by the higher pressure gas, which, in turn, shuts off the diver's supply. As a consequence of this feature, these valves are only rarely manufactured today. A downstream valve, on the other hand, opens in the same direction as the airflow, which causes such valves to be forced open by the higher pressure air. This method of operation results in smoother operation and reduced inhalation effort. Almost all commercially available regulators are now equipped with downstream second-stage valves. Many different demand regulators are available that deliver breathing gas at remarkably consistent, low-differential pressures.

5.1.1.1 Two-Stage Demand Regulators

Two-stage regulators are designed to reduce the breathing gas in a cylinder to ambient pressure in two stages. The first stage reduces the pressure to approximately 110 to 160 psi above ambient pressure, and the second or demand stage reduces the pressure from this level to ambient pressure. The major advantage of the second stage is that air is supplied to the demand stage at a nearly constant pressure, which allows both a reduction in breathing resistance and fewer fluctuations caused by changes in depth and decreasing cylinder pressure. Breathing resistance is reduced because the demand valve works against a controlled pressure (110 to 160 psi above ambient from the first stage).

All single-hose regulators are two-stage demand regulators. A few two-stage, two-hose regulators are still in use, and single-stage, two-hose regulators can be seen occasionally. The original two-stage regulator is the double-hose model similar to the original Aqualung developed by Gagnon and Cousteau in 1943, in which both pressure reduction stages are combined into one mechanical assembly that mounts on the tank manifold. Two flexible low-pressure hoses lead from either side of the regulator to a mouthpiece that contains both the inhalation and exhaust non-return valves. The hose that leads over the right shoulder supplies the breathing (inhalation) gas at ambient pressure, and the exhaled gas exits through the mouthpiece and is exhausted at the regulator through the hose leading over the left shoulder. The two-hose regulator is no longer widely used, and it is not currently in commercial production.

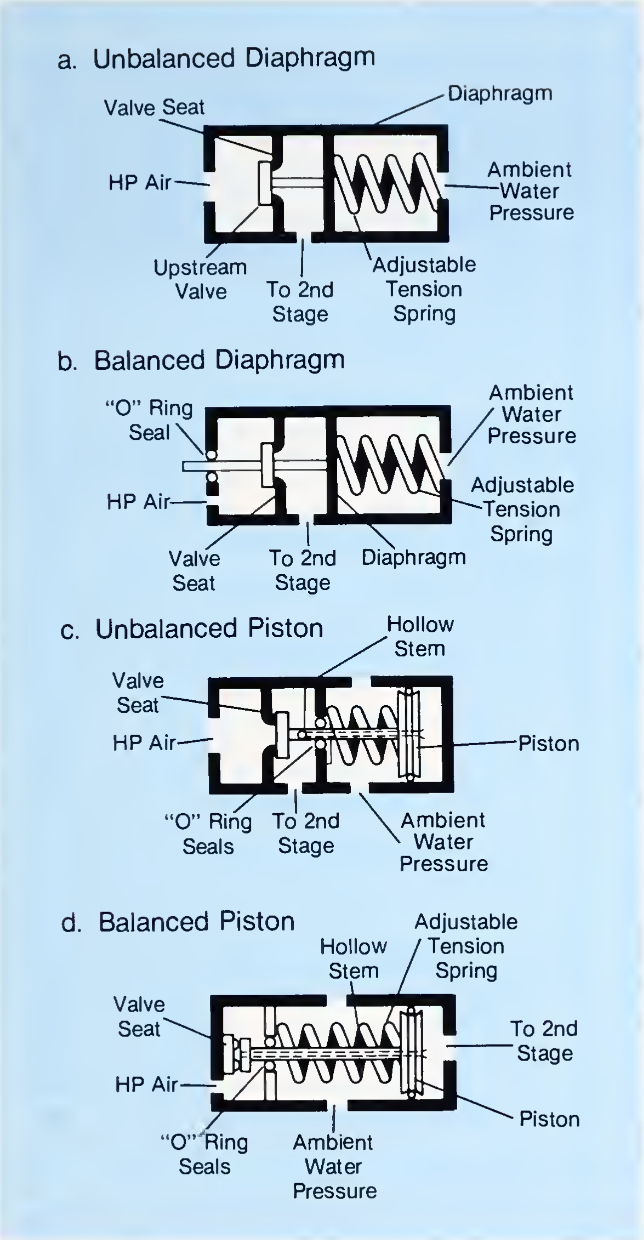
The **single-hose** regulator is designed so that the first pressure reduction stage mounts directly on the tank manifold or valve, and the second pressure reduction stage is contained in an assembly that also includes a mouthpiece and exhaust ports. The first and second stages are connected by an intermediate pressure hose. Air is delivered from the first stage at intermediate pressure (110-160 psi over ambient) and from the second stage at ambient pressure. The exhaust gas is released into the water from the mouthpiece through the exhaust port (non-return valve). The single-hose, two-stage regulator is the most common regulator in use because of its reliability, simplicity, and ease of maintenance (Cozens 1980). Lighter weight plastics are being used in second-stage housings, and silicone rubber components have largely replaced less durable materials. The performance characteristics of second-stage components have also been improved by eliminating metal-to-metal interfaces.

First-stage regulators are available in two types, **diaphragm** and **piston;** both types are produced in two configurations, unbalanced and balanced (Figure 5-2). The diaphragm first-stage regulator (Figure 5-2a) contains an unbalanced upstream valve (i.e., high-pressure air acts to close the valve). A spring applies a force that opposes that of the high-pressure air and acts against a flexible diaphragm. The forces exerted by the spring, the water (ambient), and the high-pressure air combine to activate the valve. During descent, the increasing hydrostatic pressure in the free-flooding chamber displaces the diaphragm and opens the valve until equilibrium is restored. When the diver inhales, the reduced pressure in the intermediate chamber displaces the diaphragm and opens the valve until equilibrium is achieved.

The balanced diaphragm first-stage regulator (Figure 5-2b) is designed so that the valve stem extends completely through the high-pressure chamber; the operation of the balanced valve is thus independent of the tank (supply) pressure. In both balanced and unbalanced configurations of the diaphragm first-stage regulator, failure of the diaphragm causes the valve to close.

The unbalanced piston first-stage regulator (Figure 5-2c) contains a downstream valve (i.e., higher pressure air acts to open the valve). A bias spring in the free-flooding chamber controls the intermediate pressure, and a hole in the shaft of the piston allows

Figure 5-2
First-Stage Regulators



Source: NOAA (1979)

the dry side of the piston to be equalized at the intermediate pressure. During descent, the increasing hydrostatic pressure in the free-flooding chamber displaces the piston, opening the valve until equilibrium is restored. When the diver inhales, the reduced pressure in the intermediate chamber displaces the piston, opening the valve until equilibrium is achieved.

The balanced piston regulator (Figure 5-2d) is designed so that the piston movement is isolated from the high-pressure chamber by an 0-ring; the operation of the valve is therefore independent of tank (supply) pressure. In both the balanced and unbalanced configuration, failure of the piston seal tends to cause the valve to fail in the open or free-flow mode.

The **second-stage regulator**, located in the mouthpiece, is connected to the first stage by a medium-pressure hose; this hose, in turn, supplies a constant medium pressure to a valve in the mouthpiece. The reduction in pressure in a low-pressure chamber in the mouthpiece caused by inhalation results in distortion of a diaphragm. This distortion applies pressure to a stem or linkage that is connected directly to the medium-pressure air inlet valve, opening the valve and admitting air into the mouthpiece at ambient pressure. As long as a diver inhales, air will continue to flow into the mouthpiece. In addition, most regulator manufacturers incorporate **aspirators** (venturi's) into their designs to improve the dynamic breathing characteristics of the regulator; the **venturi effect** tends to pull the diaphragm inward, which reduces inhalation effort. On exhalation, the diaphragm returns to a neutral position, releasing pressure on the stem or linkage, which returns to its normal position, closing the medium-pressure valve. As exhalation increases the pressure in the low-pressure chamber to levels above ambient, a one-way **mushroom valve** is unseated, which allows the exhaled gas to be exhausted into the surrounding water. A properly constructed second stage has a minimum of dead space, which limits the amount of air that will be rebreathed.

The **pilot valve** second stage also has been used with a number of regulators; it incorporates an air supply valve that is opened and closed by air pressure rather than by mechanical leverage. The opening pressure is generated by air flow through a diaphragm-activated downstream pilot valve. A simple mechanical linkage is used between the diaphragm mechanism and the pilot valve. Because the pilot valve is very small, the amount of spring tension needed to counterbalance the pressure is small and less force is necessary to open and close the valve. The pilot valve opens only a little way to permit the air supply valve to pass a small amount of air into a control chamber. With this system, air supply valve openings larger than those used in conventional leverage systems can be used in the second stage.

Because there is a piston opposite the valve opening that exactly counteracts the opening force of the air pressure, the supply valve is balanced and therefore is not affected by intermediate pressure variations. The system can be described as a pneumatically amplified second stage; this means that a small force, the pilot valve, is pneumatically amplified to move a larger force, the air supply valve.

The aspirator port, mentioned previously, is directed toward the mouthpiece inside the regulator and generates a slight vacuum within the regulator case when air is flowing. As a result, less effort is required to maintain air flow during inhalation. Although normally set for demand breathing, the aspirator can be set for positive-pressure breathing. The regulator is so sensitive to pressure variations that, in some cases, a dive/predive switch is incorporated to decrease the response of the regulator. Normally, a regulator requires a pressure or suction equivalent to that of a 2-inch (5.1 cm) water column to activate air flow; the pilot system requires a pressure equal to that of a 0.5-inch (1.3 cm) water column.

The operation of the regulator is initiated by a slight inhalation effort that causes the regulator diaphragm to be drawn downward. The resulting linkage movement opens the pilot valve, and air flows to pressurize the control chamber; this, in turn, opens the air supply valve. The structural arrangement between the pilot and air supply valves provides a controlling feedback that allows the air supply valve to move only in exact response to the pilot valve. The pilot valve acts as a safety relief valve in the event of first-stage malfunction. A mechanical override also is incorporated into the system to ensure operation in case the pilot valve malfunctions.

5.1.1.2 Breathing Hoses

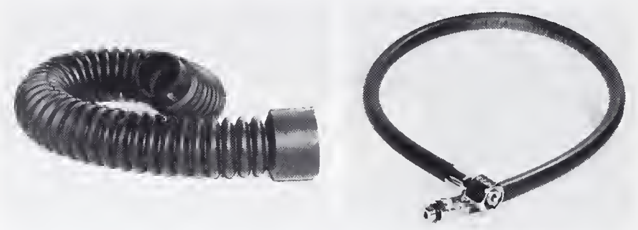
In double-hose scuba, the breathing hoses (Figure 5-3A) are flexible, large-diameter rubber ducts that provide passageways for air from the cylinder to the diver. Corrugated rubber hoses are common, but hoses may also be made of rubberized fabric with metallic rings or spiral stiffening. To provide minimum resistance to breathing, the hose should have an inside diameter of at least 1 inch (2.5 cm) and should be long enough in the "relaxed" state to allow full freedom of body movement. The hose must be capable of stretching to twice its relaxed length without collapsing or buckling.

Single-hose scuba, with the second stage of the demand regulator mask mounted or mouthpiece mounted, does not require the large-bore, ambient pressure breathing hose described above because the gas in the hose is at medium pressure (110 to 160 psi above ambient) rather than at ambient pressure (Figure 5-3B). The second-stage or demand valve is connected to a cylinder-mounted first-stage regulator by a single, medium-pressure hose of relatively small diameter. Exhaled gases are discharged directly into the water through an exhaust valve in the mask or mouthpiece.

Breathing hoses should be checked for cracks or chafing before every dive. Divers should check the connections that are covered by hose protectors especially carefully before diving, because the protectors sometimes conceal damage.

Figure 5-3
Breathing Hoses

A. Corrugated Hose B. Low-Pressure Hose Fitting



Source: NOAA (1979)

5.1.1.3 Mouthpieces

The mouthpiece (Figure 5-4) provides a channel for the flow of breathing gas between the diver and the life-support system. The size and design of the mouthpiece differ among various manufacturers, but the mouthpiece generally is molded of neoprene, silicone rubber, or other materials that have a low deterioration rate. (Silicone rubber has the added advantage of being hypoallergenic.) Typically, the mouthpiece consists of a flange that fits between the diver's lips and teeth. Bits, one on either side of the opening, serve to space the jaws. The mouthpiece should fit comfortably and be held in place when a slight pressure is exerted by the lips and teeth. The novice diver often forgets that the bits are spacers and should not, under normal conditions, be used as grips. In an emergency, the bits will provide a reliable grip, but continuous force exerted through the teeth will weaken the bits and cause considerable fatigue of the muscles around the jaws.

Many individuals have difficulty with temporal mandibular joint (TMJ) pain when gripping the mouthpiece tabs too firmly during a dive. Mouthpieces that spread the load to the rear teeth are more comfortable. Learning to relax the jaw is probably the most effective deterrent to TMJ pain.

On a two-hose regulator, the mouthpiece assembly incorporates a system of one-way check valves, and clamps are provided for the breathing hoses. In a single-hose scuba regulator, the mouthpiece is incorporated into the second-stage demand valve housing. In some cases, the mouthpiece assembly can be replaced entirely by a full face mask. The use of a full face mask in lieu of a mouthpiece facilitates voice communication by freeing the diver's mouth; however, with this configuration, an oral nasal mask must be used to prevent carbon dioxide buildup.

Figure 5-4
Mouthpieces

A. Double Hose B. Single Hose

Courtesy U.S. Divers

5.1.1.4 Check Valves and Exhaust Valves

Check valves and exhaust valves (Figure 5-5) are designed to permit gas flow in one direction only. Check valves direct the flow of inhaled and exhaled gases through the breathing system. During inhalation, pressure decreases in the mouthpiece chamber (now lower than ambient), which seats the exhalation check valve but opens the inhalation check valve. During exhalation, the air is directed out through the mouthpiece and exhalation tube to the exhaust valve. This pair of valves within the mouthpiece assembly minimizes dead air space within the system, and this, in turn, minimizes the rebreathing of exhaled gases. The inhalation check valve also prevents water from entering the demand regulator when the mouthpiece floods.

An exhaust valve is a special check valve that permits the discharge of exhaled gas from the breathing system and prevents the entrance of water. A flapper valve (also called a flutter valve) is typically used as an exhaust valve in the double-hose regulator, while a mushroom valve generally fulfills this function in the single-hose model. A flapper valve is simply a soft rubber tube collapsed at one end; when ambient water pressure is greater than the air pressure within the valve, the valve remains in the collapsed condition. During exhalation, however, the increase in pressure above ambient pressure forces the flapper open, allowing the gas to escape. Water cannot enter the valve while the higher pressure gas escapes, and when the pressure equalizes, the flapper returns to the relaxed or closed position.

The mushroom valve on single-hose models is made of extremely soft, flexible rubber, which renders it very sensitive to changes in pressure across the check valve. A wheel-shaped valve seat is fashioned to hold the rubber mushroom in place. Rigid spokes of the valve seat support the mushroom valve against a closing pressure but permit the flow of air when pressure within the mouthpiece exceeds ambient pressure.

5.1.1.5 Preventive Maintenance for Regulators

Because regulators are one of the primary components of a life-support system, they require careful maintenance. An essential element of maintenance is to ensure that no foreign matter has entered any of the regulator's components; introducing foreign matter into an area of close tolerance or into a perfect seal could cause a malfunction. The primary entry point for foreign matter is the high-pressure inlet in the first stage. For this reason, the dust cap should be kept in position over the high-pressure inlet whenever the regulator is not in use. Salt water entering the high-pressure inlet will leave deposits of salt that can prevent proper operation or pit valve surfaces. The addition of a few drops of salt water into the high-pressure filter on several successive days can substantially degrade the performance of most regulators.

Divers should be alert for early symptoms of equipment malfunction. For example, increased breathing resistance may be caused by the corrosion of internal moving parts, and water leakage in the mouthpiece can occur as the result of deterioration of the second-stage exhalation valve. Other signs that indicate problems are rusting or clogging of the first-stage filter, free flowing, and 0-ring leaks. These and other signs of trouble should be thoroughly evaluated before any further dives are made.

The most important maintenance to be performed on a regulator is a fresh water rinse after each use; this procedure removes salt and other debris (sand, dirt, etc.) from the regulator and prevents deterioration. Rinsing should be done within a few hours of the completion of a dive, regardless of whether the dive was conducted in fresh or salt water. Procedures for washing single- and double-hose regulators vary significantly and are discussed below.

With a single-hose regulator, the first stage should be held under a stream of warm, fresh water for at least 2 minutes while the dust cap remains sealed in place, and water should be allowed to flow freely through any open ports. This is especially important with piston-type regulators, because it prevents the buildup of salt on the piston tracks. Because the dust caps provided with some regulators are not watertight, the diver must make sure the cap is watertight before rinsing the regulator.

When rinsing the second stage of a single-hose regulator, the diver should permit water to enter through the mouthpiece and exit via the exhaust. Allowing water to flow in the direction of the non-return exhaust valve washes sand, dirt, etc., out of the mouthpiece. The purge button should not be pushed unless the system is

Figure 5-5
Check and Exhaust Valves

Source: NOAA (1979)

pressurized, since doing so opens the air inlet valve and might allow dirty water to pass through the middle-pressure hose to the high-pressure stage. If the regulator is to be stored for a long period of time, it may be desirable to remove the band holding the two sections of the second stage and the diaphragm in place and to rinse each separately. Rinsing procedures for the double-hose regulator are more complicated than for the single-hose model. As with the single-hose regulator, rinsing should be conducted with the watertight dust cap in place. The exhaust side of the regulator has a series of holes, and water should be allowed to flow freely through this section.

Care must be taken when rinsing the hose and mouthpiece assembly because any water that is forced under high pressure into the mouthpiece may bypass the soft rubber non-return valve and enter the intake side, which may cause corrosion. During rinsing, the mouthpiece should be held with the air inlet valve up, and water should be allowed to enter the mouthpiece, flow through the exhaust valve and hose, and exit at the main body of the regulator. To remove water from the corrugations in the hose, the hose should be stretched lightly and the diver should blow through the mouthpiece, allowing excess water to pass out through the exhaust. The regulator should not be hung by the mouthpiece, because this will stretch and weaken the hose. To avoid cultivating bacteria in the corrugations, the interior of the hoses should be dried periodically. Scuba regulators should be tested functionally on a regular basis and at least as often as every 6 months. Performing this test usually requires nothing more than a manometer.

NOTE

Hoses (especially exhaust hoses) should be removed periodically and should then be washed with surgical soap to prevent bacterial buildup.

5.2 SURFACE-SUPPLIED DIVING EQUIPMENT

One of the major constraints of scuba diving is the limited quantity of breathing gas the diver can carry; with umbilical (surface-supplied) diving, divers have a continuous air supply, which allows them to spend more time on the bottom. The increased safety provided by umbilical equipment is also important. In this mode, the diver is tethered and has direct voice communication, which permits safe operation under conditions considered too hazardous for the self-contained diver. If a surface-supplied diver becomes fouled or disabled, a continuous air supply can be maintained from the surface and a standby diver can locate the diver by following the entrapped diver's tether. In addition, if strong currents are a problem, the tethered diver can use additional weights to increase his or her stability.

Surface-supplied diving can be conducted from many locations: from the surface, a habitat, a personnel transfer capsule, or a lockout submersible. An umbilical to the diver that runs from the gas storage cylinders of the habitat, capsule, or submersible provides the diver's breathing gas, hot water (if required), and a communications link. The major disadvantage associated with surface-supplied diving is that this mode requires more support equipment and personnel than is the case for the scuba mode.

Many safe and efficient diving masks and helmets are available commercially. All masks and helmets provide the diver with a continuous supply of breathing gas, and some models allow the diver to elect either the free flow or demand operating mode. A communication system is standard equipment on modern surface-supplied helmets.

5.2.1 Free Flow/Demand Masks

The free flow/demand mask is designed to be used with an umbilical hose that supplies breathing gas from the surface, an underwater habitat, or a personnel transfer capsule (submersible decompression chamber). Free flow systems supply sufficient ventilation for heavy work and also provide divers with an adjustable-flow, off-on supply to the interior of the mask through the muffler deflector. In addition to supplying the diver with a steady flow of breathing gas, the deflector directs gas across the viewing lens to prevent fogging. When the umbilical hose is pressurized with breathing gas, the demand regulator is pressure-loaded at all times. The regulator provides a demand breathing system, similar to that of standard open-circuit scuba, which is adjustable for gas supplied at pressures ranging from 60 to 180 psi over ambient pressure. Demand systems are preferred for light to moderate work because they economize on gas requirements and enhance communication. A nose-blocking device is incorporated into demand systems to facilitate sinus and middle-ear equalization, and an oral-nasal mask assembly is used to reduce dead air space and eliminate the possibility of a dead air space carbon dioxide buildup.

Some lightweight masks and helmets conventionally used for surface-supplied diving are equipped with regular scuba demand regulators and can be adapted easily for use with self-contained air supply (scuba tanks). Divers using these masks consume more air than they do with regular scuba mouthpieces, and each diver's air consumption rate should be determined at several different work loads before actual diving operations begin. To permit buddy breathing, an octopus second-stage regulator can be added to the first stage. The advantages of this setup are greater comfort around the mouth and jaws during long exposures and the ability to utilize a tape recorder or diver-to-diver communication.

Face masks may be equipped with nose-blocking devices to facilitate equalization of pressure during descent. Blocking off the nose to aid in equalizing pressure in the ears is accomplished easily either by pushing upward on the bottom of the mask to create a seal or gripping the nose when using masks with nose pockets. Masks also may be equipped with a purge valve to aid in clearing water from the mask. Only high-quality masks with large purge valves are recommended, because purge valves are subject to failure or leakage.

Face mask selection is a matter of individual preference, fit, comfort, and other diver requirements. Masks are available in a variety of sizes and shapes that will accommodate different lens configurations. The closer the lens is located to the eye, the wider the peripheral visual field (Egstrom 1982). Selection of a mask that fits well can provide easy clearing and an optimal visual field. A problem with some of the new clear plastic or clear rubber masks is that they allow light to enter from the side, which may cause a mirror effect on the lens.

The following features should be looked for when selecting a face mask:

- Light weight
- Comfortable fit
- Wide-angle vision
- Easy closure of nostrils for equalization
- Low volume
- Easy strap adjustment
- Secure strap fasteners
- Hypo-allergenic material
- Tempered safety glass.

Divers who must wear eyeglasses on land generally need some form of optical correction under water. Several methods for accommodating corrective lenses in divers' face masks have been developed:

- Individual prescription lenses can be inserted into goggle-type masks;
- Prescription lenses can be incorporated into the faceplate;
- Large-size prescription lenses can be bonded permanently to the inner faceplate surface;
- Lenses can be mounted in a special frame and be secured to the inside of the faceplate;
- Standard glasses can be mounted inside the faceplate with stainless steel spring wire; and
- Soft or fenestrated contact lenses can be worn.

Each of these methods has advantages and disadvantages. Glasses generally cannot be worn inside a mask because the temples cause the mask to leak. Wearing lens inserts inside the face mask is simple and inexpensive but provides an extra surface to fog. Some off-the-shelf masks are available with built-in correction; whether or not these are useful to a given individual depends on several factors, including the type and amount of refractive error, the similarity of error in the two eyes, and the interpupillary distance.

The use of contact lenses under the face mask provides good vision under water, offers a wide field of view, and eliminates problems with fogging. However, some people do not tolerate contact lenses well, and some lenses cause corneal edema. The signs and symptoms of corneal edema, which include discomfort, haloes around lights, and loss of visual acuity, have been found to occur when unfenestrated hard contact lenses are used; soft lenses or fenestrated hard lenses do not cause this condition, which has been attributed to the inability of hard lenses to "breathe" (Simon and Bradley 1978, 1980). Because a dislodged lens can be very painful and debilitating, Cotter (1981) has suggested that dive buddies establish a signal that means "lens or eye trouble" if either diver wears contact lenses. (The options available to individuals who have different types of refractive error but wish to dive, and the advantages and disadvantages of the various methods, are discussed fully in Kinney (1985).)

Ventilation across the faceplate generally is poor, and the glass tends to fog easily. To minimize fogging, the inside of the faceplace should be smeared with saliva and then be rinsed before wearing. Anti-fogging solutions (such as a mild liquid soap or a special commercial preparation) may be applied to the inside of the faceplate. The faceplate should be washed frequently in detergent to remove oils or surface film, both of which enhance fogging. If the mask fogs during use, drops of water should be let into the mask and should then be rolled across the fogged areas to clear them.

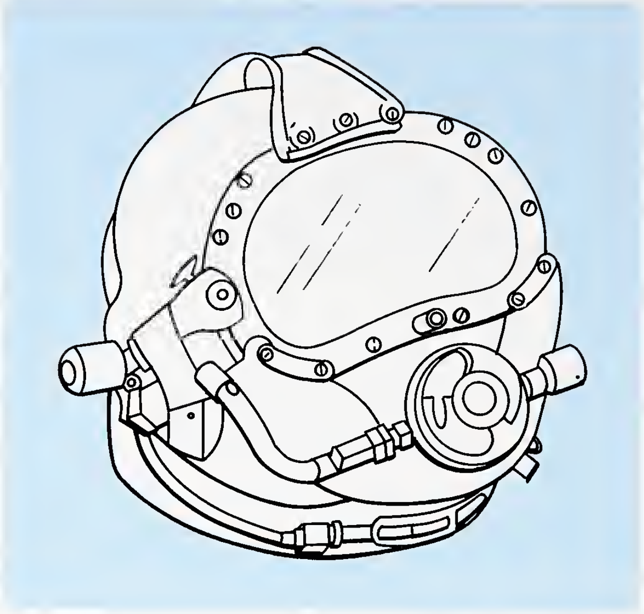
If the mask has a purge valve, the valve should be thoroughly washed out to remove any sand that might prevent it from sealing properly. The mask should not be left in the sun for any extended period because sunlight will make the headstrap and sealing edge brittle. Although the headstrap can be replaced easily and economically, cracking of the sealing edge will make the mask useless.

Self-contained emergency gas supply systems (or bailout units) are used in conjunction with surface-supplied diving equipment to perform work at depths in excess of 60 feet (18.3 m), when working in tunnels, pipes, etc., or where there is the danger of entanglement. These units consist of a scuba cylinder assembly, a reduction regulator (i.e., first stage of a standard single-hose regulator), and a backpack-harness assembly. The capacity of the scuba cylinder assembly varies from 10 ft^3 to 140 ft^3, depending on the diver and the situation. Emergency gas may be fed directly into the diver's mask through a special attachment on the side valve or be introduced directly into the diver's air hose assembly. In the latter case, a check valve must be located between the intersection of the emergency gas supply hose and the primary surface supply hose. A completely separate bailout system, which includes a scuba tank and regulator, may be used. If the umbilical air supply is lost, the full face mask must be removed before the diver ascends to the surface using the scuba tank and mouthpiece. If an emergency gas supply system is selected, a second face mask should also be carried. The advantage of this configuration is complete redundancy; the disadvantages are loss of communication and difficulty in putting on the face mask and locating the regulator.

5.2.2 Lightweight Free Flow Helmets

Many lightweight free flow diving helmets have been designed and manufactured in recent years. Some manufacturers have constructed helmets of the traditional spun copper, which emphasizes indestructibility, while others use fiberglass and emphasize comfort, light weight, and maneuverability. In general, modern lightweight helmets (Figure 5-6) feature streamlined design, standardized interchangeable fittings, improved valves, unbreakable faceplates, better ventilation (low CO_2 buildup), improved visibility, better communication, versatility because they can be used with any type of dress, bailout capability, and simplicity of use and maintenance. Modern helmets can be used with a neoprene wet suit, a hot-water suit, or a variable-volume suit. Some helmets attach to the neck bands of specially adapted dry suits for use in cold or contaminated water.

Figure 5-6
Lightweight Helmet



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5.2.3 Lightweight Free Flow/Demand Helmets

Free flow/demand system dry helmets combine the advantages of full head protection, communications, and the breathing characteristics of a standard dry helmet with the gas economy and comfort of a demand mask. Weight is distributed throughout the helmet to achieve balance and optimum performance without neck strain or effort. The helmet is designed to be neutrally buoyant in seawater. It is equipped with an auxiliary (or emergency) system valve and a non-return valve and with communication earphones and microphone. An oral-nasal mask reduces the potential for CO_2 buildup.

5.2.4 Umbilical Assembly

The umbilical assembly for surface-supplied lightweight helmets and free flow/demand masks generally consists of a gas supply hose, a pneumofathometer hose, a communications wire, and a strength member. Depending on dive requirements, a hot-water supply hose may also be included. Umbilical members are assembled in continuous lengths; for example, in shallow water diving operations (i.e., to depths less than 90 fsw (27 m)), a 150-foot (45 m) assembly may prove satisfactory. Regardless of length, all members should be in continuous lengths because umbilical assemblies designed with fittings and connectors have a greater likelihood of failing or separating.

5.2.4.1 Gas Supply Hoses

A 3/8-inch (1.2 cm) or larger synthetic rubber, braid-reinforced, heavy-duty hose is generally used to carry the diver's air supply. The hose must have a working pressure of at least 200 psig (this pressure must exceed the diver's required supply pressure). The outer cover of the hose must be durable and resistant to abrasion, weathering, oil, and snag damage. The inside tube of the hose must be non-toxic and impervious to any breathing gas to be used. Hoses must be flexible, kink resistant, and easy to handle. Although a hose may have a sufficient pressure rating, it may shrink considerably in length because it increases in diameter when pressurized, which causes looping of the other members of the umbilical assembly. To avoid problems, the percentage of shrinkage should be determined before purchasing the hose, and the assembly should be taped while the hose is pressurized. At pressures less than 150 psig, the change in length should not exceed 2 percent.

To facilitate recordkeeping, all air supply hoses should be tagged with a serial number. A metal tagging band that is resistant to damage and unlikely to be lost during use is desirable. Purchase, test, and usage records should be maintained for each hose assembly.

5.2.4.2 Communication Cables

Communication cables must be durable enough to prevent parting when a strain is placed on the umbilical assembly; they must also have an outer packet that is waterproof and oil- and abrasion-resistant. Multiconductor shielded wire (size 14 to 18) that has a neoprene outer jacket is satisfactory for shallow water diving. In normal service, only two conductors are used at any one time. The wire-braid shielding adds considerable strength to the umbilical assembly. The cable should be in a continuous length, with an additional few feet at the diver's end and the surface end to allow room to install connectors, make repairs, and connect the communication equipment.

The wire is fitted with connectors that are compatible with those on the helmet or mask. A four-conductor, waterproof, "quick-connect" connector is often used; these connectors have a socket-type configuration. When joined together, the four electrical pin connections are established and a watertight seal is formed, which insulates the wire from the surrounding seawater. To be secure and waterproof, these connectors should be molded to the communication cable. Professional installation is desirable. For field installation, rubber electrical tape overlaid with plastic electrical tape has been successful, although it is less satisfactory than special molding processes. The surface end of the wire should be fitted with an appropriate connector, generally of the standard terminal post type, that is compatible with the communications unit. Many divers use simple terminal or binder post connections on masks and helmets. The ends of the wire are prepared with solder, inserted into the binder post terminal, and secured. Although less satisfactory than the special connectors mentioned above, the use of terminal or binder post connections is satisfactory and economical.

Standard two-wire "push-to-talk" communicators are commonly used in diving. By using all four wires in the communication wire, the system can be set up so that the diver's voice is "live" at all times. All communication wires should be tagged or coded for recordkeeping purposes, and lines should be checked before being issued for use on any dive.

5.2.4.3 Pneumofathometer Hoses

The pneumofathometer hose is a small hose that is open at the diver's end and connected to an air source and pneumofathometer at the surface. Pneumofathometers are precision pressure gauges that are calibrated in feet of seawater and are used to determine the precise depth of the diver under water. Pneumofathometers must be protected from abuse and should be calibrated regularly. Lightweight air or oxygen hose (0.24-in. (0.6 cm) i.d., 200 psig working pressure) is generally used. Standard oxygen fittings are used for surface connections.

5.2.4.4 Strength Members

The U.S. Navy recommends the use of a strength member in the umbilical assembly. The lines used as strength members include:

- 3/8-in. (1.2 cm) nylon braided line
- 3/8-in. (1.2 cm) synthetic polyolefin braided or 3-strand twisted line

- 3/8-in. (1.2 cm) manila line
- thin stainless aircraft-type cable.

Each type of line has advantages and disadvantages. Braided nylon line is commonly used and has acceptable strength, durability, and handling qualities, although it stretches under high load conditions; many organizations, including the U.S. Navy, use this type of line. Polyolefin line floats and thus reduces the in-water weight of the umbilical assembly somewhat, but this type of line can be abrasive to the hands. Manila line is readily available and is the least expensive, but it deteriorates rapidly. Aircraft-type cable is strong, compact, lightweight, and expensive. Some divers use hollow-core polyolefin line, with the communications line running through the hollow core, to combine the strength and communication members. A few combination strength member/communicator wire lines are commercially available.

5.2.4.5 Hot-Water Hoses

When hot-water wet suits are worn on a dive, a specially insulated hose is required. This hose can be obtained in either 1/2- or 3/4-inch (1.2 or 1.8 cm) inside diameter size, depending on the depth and volume of water to be supplied to the diver. The insulation reduces the loss of heat to the open sea, which allows a lower boiler operating temperature. The hose should be equipped with a quick-disconnect female fitting that is compatible with the manifold attached to the suit. To prevent handling problems, the hot-water hose should be joined to the diver's gas and communications umbilical.

5.2.4.6 Assembly of Umbilical Members

The various members of the umbilical assembly should be bound together with pressure-sensitive tape. Two-inch (5 cm) wide polyethylene cloth-laminated tape or duct tape is commonly used. Prior to assembly, the various members should be (1) laid out adjacent to each other, and (2) inspected for damage or abnormalities; all fittings and connections should be installed in advance. The gas supply hose and pneumofathometer hoses should be connected to the air supply and should be pressurized to about 150 psig to ensure that shrinkage does not cause looping.

The following guidelines should be observed when assembling umbilical members:

- The strength member should terminate in a position to hook to the diver's safety harness, generally on the left-hand side, so that the strain of a pull from the surface is placed on the harness and not on the diver's helmet, mask, or fittings.
- If a lightweight, more flexible "whip" (short length of hose) is used between the helmet and the main umbilical air supply hose, the communication line and the supply hose should also be adjusted accordingly.
- If a whip and special auxiliary air supply line valve are used for helmet diving, their length should be adjusted.

The diver should have sufficient hose and cable length between the safety harness attachment point and the mask (or helmet) to allow unrestricted head and body movement without placing excessive stress on the hose connections. Excessive hose should not, however, form a large loop between the harness connection and the mask.

The communication line should be slightly longer than the rest of the assembly to permit repairs at the diver's end. The diver's end should be fitted with a snap hook that is secured to the strength member and the rest of the assembly to facilitate attachment to the safety harness. The surface end of the strength member and other components also are secured to a large D-ring, which allows the assembly to be secured at the diving station.

5.2.4.7 Coiling and Storage of Umbilical Hose

After the umbilical hose is assembled, it should be stored and transported; protection should be provided for hose and communications fittings during these procedures. The hose ends should be capped with plastic protectors or be taped closed to keep out foreign matter and to protect threaded fittings. The umbilical hose may be coiled on take-up reel assemblies, "figure-eighted," or coiled on deck with one loop over and one loop under. Incorrect coiling, all in the same direction, will cause twist and subsequent handling problems. The tender should check the umbilical assembly at the end of each dive to ensure that there are no twists, and the coil should be secured with a number of ties to prevent uncoiling during handling. Placing the umbilical assembly in a large canvas bag or wrapping it in a tarpaulin will prevent damage during transport.

5.2.4.8 Umbilical Maintenance

After a day's diving, the umbilical should be washed with fresh water, be visually inspected for damage, and be carefully stored to prevent kinks. If the umbilical is to be stored for a long period of time, the hoses should be blown dry and the connectors should be capped to prevent foreign matter from entering. Connectors should be lubricated with silicone spray after capping.

5.2.4.9 Harness

The diver should wear a harness assembly to facilitate attachment of the umbilical assembly. The harness should be designed to withstand a minimum of a 1000-pound (454 kg) pull in any direction, and it must prevent strain from being placed on the diver's mask or helmet when a pull is taken on the hose assembly. The location of the attachment depends on the type of harness assembly worn by the diver, but the harness should not be attached to the weight belt in case the latter needs to be dropped.

WARNING

Never Attach the Diver's Umbilical Directly to the Weight Belt. A Separate Belt or Harness is Required To Permit the Weight Belt To Be Dropped If Necessary

5.2.4.10 Weighting Surface-Supplied Divers

To weight the diver properly, lead weights (3, 5, or 8 lbs (1.4, 2.3, or 3.7 kg) each) are secured to the belt with bolts. The belt is approximately 4 inches (10.2 cm) wide and is fitted with a quick-release fastener. The weight belts used for arctic diving are heavier than most belts because of the bulk and positive buoyancy of cold-water exposure suits. A shoulder harness that is similar in configuration to a fireman's suspenders is the best method of preventing the heavy, unwieldy belts from slipping off. If a leather belt is used, it should be coated regularly with neat's-foot oil.

Weighted shoes or leg weights may be used in conjunction with the weight belt (primarily by tethered divers) to overcome positive buoyancy and to give stability to the diver. Standard weighted shoes consist of a lead or brass sole, leather straps to hold the shoe in place, and a protective brass toe piece.

Leg weights consist of one large or several small weights attached to leather or nylon straps. The straps are fitted with buckles for securing the weights to the diver's legs near the ankle. The weights vary from 2 to 10 pounds (0.9 to 4.5 kg) each, depending on the diver's preference. Leg weights provide improved stability and protection against blowup, because divers wearing variable-volume suits can swim with relative ease while wearing fins and leg weights. For safety, the weight belt should be worn outermost so that it can be freed easily when released. The only maintenance required for weight belts is fresh-water washing after use and predive checks of the quick-release mechanism to ensure that it is operating properly.

5.3 DIVER EQUIPMENT

The on-scene dive master determines which items of equipment are required to accomplish the particular underwater task. Unnecessary equipment should be left on the surface because excessive equipment can become a hazard rather than an asset. This is particularly true when diving in a strong current, under conditions of limited visibility, or in heavy surge, because each additional item of diving equipment (especially additional lines) increases the probability of fouling the diver.

Diver equipment considered in this section includes face masks, flotation devices, weight belts, knives, and swim fins. The sections below discuss each of these items in turn.

5.3.1 Face Masks

Face masks are used to provide increased clarity and visibility under water by placing an air space between the diver's eyes and the water. There are two general classes of face masks: separate face masks and full face masks (Figure 5-7) (Hall 1980a). The separate mask, which covers only the eyes and nose, is generally used for scuba diving (when equipped with a mouthpiece) or for skin diving. Full face masks are used with special scuba and surface-supplied diving apparatus. Full face masks consist of a faceplate, a frame, and a headstrap. The faceplates are made of highly impact-resistant, tempered safety glass. (Glass is still better than plastic, because plastic faceplates are subject to discoloration, abrasive damage, and fogging.) The frame is designed to hold the faceplate and to provide a watertight seal; it is usually made of plastic. Silicone rubber has largely replaced less durable materials as face seal components; the widespread use of silicone materials in diving has significantly extended the useful life of most rubber components. The mask should be sufficiently rigid to hold the rubber plate away from the diver's nose and should be pliable enough to ensure perfect fit and still retain its shape. An adjustable rubber headstrap approximately 1 inch (2.5 cm) wide and split at the rear holds the mask to the diver's head.

5.3.2 Flotation Devices

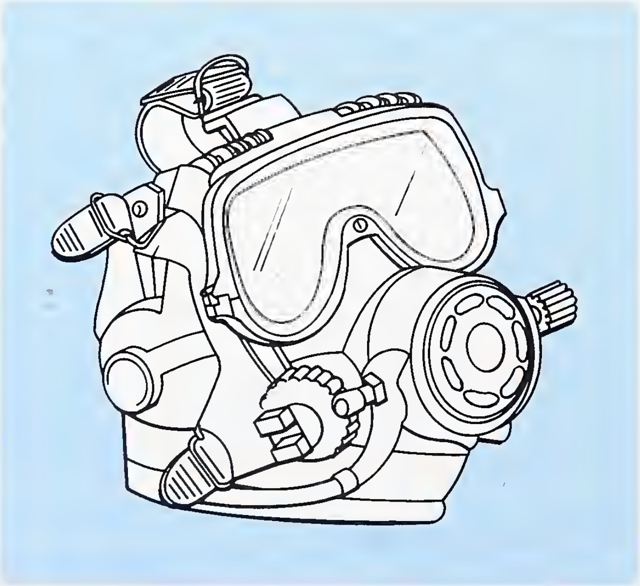
A flotation device is an essential part of a diver's life-support and buoyancy control system; it is also an

Figure 5-7
Face Masks

A. Separate Masks

Courtesy Glen Egstrom

B. Full Face Mask



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item of rescue and safety equipment. Many different buoyancy compensators have been developed during the past few years, including those with the popular stabilizing jacket and compensators using the horse collar designs (Figure 5-8). These devices are available as vest units, backpack-mounted units, stabilizer jackets, and in a wide range of variable-volume dry suits. Although almost all divers would agree that some type of buoyancy compensation is necessary, they would not agree about which configuration or design is best.

When selecting a buoyancy compensator (BC), a number of factors must be considered, including: type of exposure suit, type of scuba cylinder, diving depth, characteristics of the breathing equipment, nature of diving activity, and type of accessory equipment and weight belt (Snyderman 1980a, 1980b). The BC must be compatible with the exposure suit.

NOTE

Buoyancy compensators should not be used as a substitute for swimming ability and physical fitness.

Flotation devices should be designed so that a diver, even when unconscious, will float with face up. The inflating mechanism of the device should be constructed of corrosion-resistant metal, and a relief valve should be part of the device when it is used for buoyancy compensation. Most devices are designed to inflate automatically either when a CO_2 cartridge is punctured or when filled with air supplied by a low-pressure hose from the scuba cylinder. Regardless of their method of inflation, all flotation devices should be equipped with an oral inflation tube. The oral inflation tube should have a large diameter and be able to be operated with either hand.

Recent studies have determined that a minimum of 25 pounds (11 kg) of positive buoyancy is required to support a fully outfitted diver operating in Sea State 1 conditions. To achieve this, a 19-25 gram CO_2 cartridge must be used with a properly designed buoyancy compensator. U.S. Coast Guard regulations require life vests to have a positive buoyancy of 24.5 pounds (11 kg) to support a fully clothed adult. Divers and boat operators should keep themselves informed about the status of life vests (personal flotation devices), because, for example, the Coast Guard recently issued a warning cautioning against the use of Type III life vests in rough water because they will not keep a diver's head clear in choppy water. Flotation devices that use

Figure 5-8
Flotation Devices

Courtesy Glen Egstrom

larger cartridges than those required, multiple cartridges, and one or two inflation compartments are also available; these models can be used as buoyancy compensators if the diver partially inflates the device through the oral or power inflation tube while he or she is still submerged.

Specially designed buoyancy compensators that have large oral inflation tubes and separate inflatable chambers are commercially available. A large cylinder of compressed air that is chargeable from a standard scuba air cylinder is an integral part of some buoyancy compensators; this arrangement allows for partial or complete inflation while the diver is submerged. Pressure relief valves are provided for each compartment to prevent overinflation.

Training divers in the use of specific BC devices is essential because these devices vary widely in terms of control locations, control operation, and potential buoyancy. Regardless of the diver's choice, training and practice under controlled conditions are required to master buoyancy compensation procedures. Divers must be trained not to use excessive weights or to be overly dependent on a BC to compensate for diving weights. Because rapid, excessive inflation can cause an uncontrolled ascent, divers must learn to vent air from the compensator systematically during ascent to maintain proper control.

After each use, the exterior of the device should be rinsed thoroughly with fresh water. Special attention should be given to the CO_2 release mechanism, oral and power inflators, and other movable mechanical parts to ensure that they operate freely and easily. The CO_2 actuating lever, with cartridge removed, should be worked up and down while fresh water is being flushed through the mechanism. The mechanical parts should be allowed to dry and should then be lubricated with a silicone lubricant. The threads on the CO_2 cartridge should also be lubricated.

The most frequent cause of flotation device malfunction is corrosion caused by salt water entering the inflation compartments; the resulting residue can block the passage of CO_2 and cause significant deterioration of the inflation-release mechanism. If this occurs, the device should be filled approximately one-third full of warm fresh water, the water should be circulated rapidly through the vest, and the water should then be drained out through the oral inflation tube. Fresh water also should be flushed through the passage between the vest and the CO_2 cartridge.

NOTE

Buoyancy compensators should not be worn with a variable-volume dry suit if the BC hinders easy access to the suit's valves.

Periodic checks of the inflation device are also required. The device should be inflated and hung up over night and/or be submerged periodically to check for leaks. If leaks are observed, they should be repaired before the device is used again. The CO_2 cartridges should be weighed frequently to ensure that they have not lost their charge; if their weight is more than 3 grams less than the weight printed on the cylinder, the cartridge should be discarded. The cartridge used in a flotation device should be the one designed to be used with that device. Cartridges should also be inspected to ensure that the detonating mechanism has not punched a pinhole into the top of the cartridge that has allowed the CO_2 to escape.

WARNING

Buoyancy Compensators Should Not Be Used As Lift Bags Unless They Are Not Attached To the Diver

5.3.3 Weight Belts

Divers use weight belts to achieve neutral buoyancy; they should carry enough weight so that their buoyancy at the surface is slightly negative with a full tank and becomes slightly positive as air is consumed. The positive buoyancy provided by the diver's suit is probably the largest contributing factor in determining appropriate weight requirements. Without an exposure suit, most divers can achieve neutral buoyancy with less than 5 pounds (2.3 kg) of weight, whereas 10 to 30 pounds (4.5 to 13.5 kg) may be required, depending on depth, if a full suit is worn. Dry suits may require even more weight. Divers must accurately determine their weight requirements in shallow water before undertaking a working dive. Failure to establish the proper buoyancy can consume air and energy unnecessarily. The following test can be performed to determine the proper amount of weight to be carried: a full lung of air at the surface should maintain a properly weighted diver at eye-level with the water; exhalation should cause the diver to sink slowly, while inhalation should cause a slow rising back to eye-level with the water. (This test should only be performed on the last dive of the day because it will influence the diver's repetitive dive status.) As a general rule, the deeper the dive, the less weight will be required to achieve the desired buoyancy because of the exposure suit's compressibility. When using exposure suits with increased thickness or air spaces, care should be taken to ensure that the diver has adequate weight to permit a slow, easy ascent, especially during the last 10 feet (3 m) of ascent.

5.3.4 Diver's Knife

A diver's knife serves a variety of purposes, the most common being to pry and probe at underwater rocks, organisms, etc., and to free the diver in the event of entanglement (Boyd 1980). A diver's knife should be constructed of a corrosion-resistant metal, preferably stainless steel. Handles must provide a good, firm grip and be resistant to deterioration. The knife should be worn where it is easily accessible in an emergency; knives are worn on the inside of the calf or on the upper arm. Carrying the knife on the inside of the calf is popular because this position makes it readily accessible with either hand and lessens the likelihood that the knife itself will foul. This placement also maintains a clear drop-path for the weight belt. After each use, the knife should be rinsed with fresh water, dried, and coated with a layer of light oil prior to storage. The knife must be checked frequently to ensure that the blade is sharp; if properly maintained, the material used in most diving knives will retain a good cutting edge for a long time.

5.3.5 Swim Fins

Swim fins (Figure 5-9) increase the propulsive force of the legs and, when used properly, conserve the diver's energy and facilitate underwater movement. They are available in a variety of sizes and designs.

In general, there are two styles of fins: swimming and power (Hall 1980b). Swimming fins are smaller, of lighter weight, and are slightly more flexible than the power style, and they use approximately as much force on the up-kick as on the down-kick. The swimming-style fin is less fatiguing for extensive surface swimming, less demanding of the leg muscles, and more comfortable. Power-style fins are longer, heavier, and more rigid than swimming fins. They are used with a slower, shorter kicking stroke, with emphasis on the down-kick. This style of fin is designed for maximum power thrusts of short duration, and these fins sacrifice some comfort; power fins are the preferred style for working divers. A narrow, more rigid fin provides the best thrust-to-energy cost ratio. The fin must fit comfortably, be sized properly to prevent cramping or chafing, and be selected to match the individual's physical condition and the nature of the task to be performed. Swim fins with adjustable heel straps either should have the straps reversed, with the bitter ends inside, or the ends of their straps taped down before diving in kelp beds, surf grass, or pond weeds. If this is not done, plants may catch in the straps and impede further progress. A number of plastic fins have gained popularity because of their good propulsion characteristics and light weight; these fins couple a plastic blade with a neoprene rubber foot pocket and an adjustable heel strap.

Figure 5-9
Swim Fins

Courtesy New England Divers, Inc.

5.4 PROTECTIVE CLOTHING

Divers usually require some form of protective clothing. This clothing, known as a suit or insulation, minimizes thermal exposure effects. In addition, it protects the diver from abrasions and minor bites.

Suits must be selected with certain diving conditions in mind; elements to consider include water temperature, depth, and activity level. The following points should be considered when evaluating thermal needs:

- All insulation is trapped air or gas.
- Cold water absorbs heat 25 times faster than air.
- Fifty percent of the average diver's energy is consumed just trying to keep the body warm.
- The greater the temperature difference between the body and the surrounding water, the faster heat leaves the body.
- The larger the body mass, the better the heat retention.
- It takes time, rest, and food to replace lost heat energy.

5.4.1 Wet Suits

The neoprene wet suit is the most common form of protective clothing in use (Figure 5-10). It provides thermal protection, as well as protection against coral, stinging coelenterates, and other marine hazards. Wet suits are constructed of closed-cell foamed neoprene and generally are 3/16- or 1/4-inch (approximately 0.6 cm) thick, although suits as thin as 1/8 (0.3 cm) and as thick as 3/8 of an inch (1.2 cm) are available. Wet suits rely on air bubbles in the closed foam to act as insulation. Because the foam is compressible, however, the suit rapidly loses its insulative capability as depth increases. For example, one-half of a wet suit's insulating capacity is lost at 33 feet (10 m), two-thirds at 66 feet (20 m), and three-fourths at 99 feet (30 m). Consequently, wet suits are recommended only for shallow water diving or snorkeling and generally are not recommended for diving in water at temperatures below 60°F (15.6°C).

The wet suit used in warm water consists of neoprene pants and jacket, with optional boots, gloves, hood, and vest. For warm-water (80°F; 26.7°C) diving, a brief vest that covers only the body's trunk is available. Full-length styles that cover the entire body (including the hands, feet, and head) except the face are available for use in colder waters. Fit is important to the effectiveness of a wet suit; some divers may need a custom suit to achieve proper fit. Thinner suits provide more freedom of movement, while suits of thicker material provide better thermal protection. Most suits use a nylon liner on the inside surface of the neoprene to limit tearing and to facilitate easy entry. Models are available with nylon on both the inner and outer surfaces to minimize tears and damage to the suit; however, the added layer of nylon further restricts the diver's movements, as do elbow and knee pads. Although wet suits with nylon inside offer easier entry into the suit, they also allow water to seep in, which may be a problem in cold water. Nylon on the outside cuts down on suit abrasions but tends to hold water, which acts as an evaporative surface and causes chilling when the diver is on the surface.

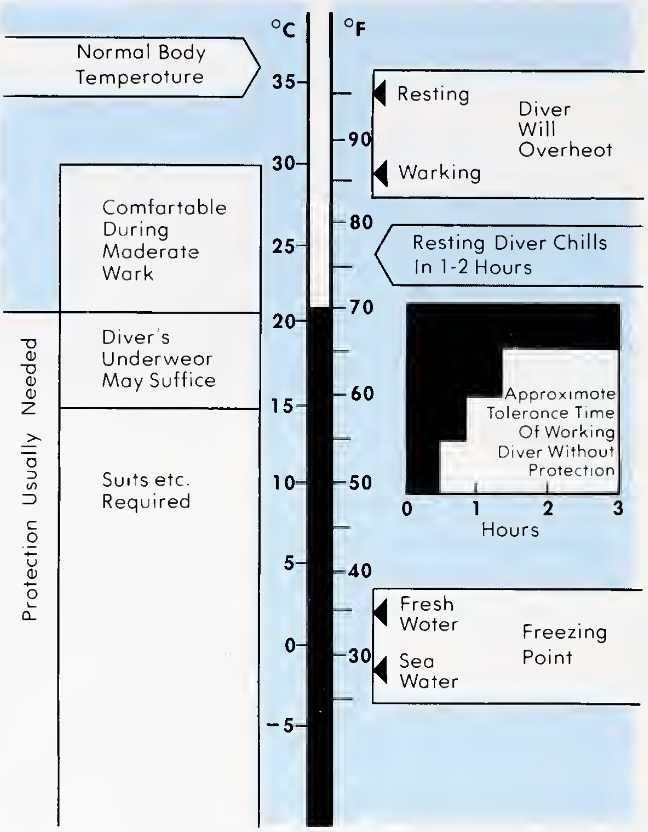
Figure 5-10
Neoprene Wet Suit

Courtesy Diving Unlimited International

The sections of a wet suit are joined by neoprene glue. The seams on better models are sewn together to prevent separation. Neoprene glue is available in small cans for quick and easy wet suit repair. However, double-surface nylon does not repair well with ordinary cement, so tears in this material should be sewn. A wet suit may have as many as five zippers, one in each ankle and sleeve and one in the front of the jacket. In colder waters, zippers can become a significant source of heat loss, and care should be taken either to minimize zipper length and number or to provide waterproof zippers if extended cold-water work is anticipated. Some suits are flexible and strong enough to be constructed without ankle and sleeve zippers.

When water temperatures approach 60°F (15.6°C), the hands, feet, and head lose heat at a rate that makes

Figure 5-11
Effects of Water Temperature



Source: NOAA (1979)

diving without protective gloves, boots, and a hood impractical. Even in tropical climates, divers often elect to wear some form of boot and glove for abrasion protection. In colder waters, loss of body heat from these body areas may significantly affect diver performance unless some form of thermal protection is worn (Figure 5-11).

Thermal protection of the hands is necessary because loss of dexterity significantly reduces a diver's effectiveness. Most divers in temperate climates prefer cotton gloves because these gloves do not severely restrict finger movement and touch. Five-fingered foamed neoprene gloves are available in 1/8- or 3/16-inch (0.3 to 0.4 cm) thicknesses that permit a satisfactory degree of finger movement. Three-fingered "mitts" are used in cold water (Figure 5-12). Proper fit is important because too tight a fit will restrict blood circulation and increase the rate of heat loss.

Failure to wear a hood in cold water can result in numbing of the facial areas and a feeling of extreme pain in the forehead immediately on entering the water, phenomena that persist until the head becomes acclimated to the cold. Fifty percent of body heat can be lost from the head and neck during submersion in cold water. Hoods that are attached to jackets generally provide better thermal protection than separate hoods. The hood should have an adequate skirt, one that extends at least midway onto the shoulders, to prevent cold water from running down the spine. In extremely cold water, a one-piece hooded vest is recommended. Fit is important when selecting a hood because too tight a fit can cause jaw fatigue, choking, headache, dizziness, and inadequate thermal protection.

Wet suits must be properly cared for and maintained if they are to last for a reasonable length of time. After each use, the suit should be washed thoroughly with fresh water; it should then be allowed to dry before being stored. The suit should be inspected carefully for rips; if any are found, the suit should be repaired before being used again. A suit can be used approximately 10 minutes after it has been repaired, but for best results it should not be used for several hours. Suit zippers and metal snaps should be inspected frequently and be kept corrosion free.

Special silicone greases are available for use as equipment lubricants; petroleum-based products will cause neoprene materials to deteriorate. Suits should be hung on wide, specially padded hangers to prevent tearing. They may also be rolled up or laid flat, but they should not be folded because prolonged folding may cause creasing and deterioration of the rubber at the folds. Suits should be stored out of direct sunlight because prolonged exposure to the sun will cause the neoprene to rot, become brittle, and crack. Storing suits in hot, dry environments also can lead to deterioration.

5.4.2 Dry Suits

Dry suits that are made of waterproof materials are becoming more widely used than wet suits. Commonly called shell suits, these fabric suits are designed to be worn with undergarments; they are usually used with hoods and gloves and are relatively easy to doff and don.

Dry suits can be inflated via the inlet valve on the diver's air supply at the low-pressure fitting on the regulator, and air inside the suit can be expelled through an exhaust valve. Some valves are equipped with an adjustable over-pressure relief mechanism, which allows for automatic buoyancy control. By manipulating the valves, a properly weighted diver can maintain buoyancy control at any depth. A power exhaust valve can evacuate excess air from the suit, which makes the suit easier to deflate. Because shell suits have no inherent flotation capability, a buoyancy compensator that does not cover the suit's valves should be worn.

Dry suits must be maintained properly. They should be washed with fresh water after each use, and water

Figure 5-12
Cold-Water Mitt, Liner Included

Courtesy Trelleborg/Viking Inc.

should be sprayed directly into the suit's valves to wash out sand. If the suit develops mildew spots, it should be washed with soap and water. Finally, the suit should be allowed to dry while hanging so that it will dry thoroughly inside and out.

Dry suits should be stored away from sunlight and from ozone-producing sources, such as cars or gas-fired household water heaters. The life of the suit's seals can be extended by storing the suit in a dry plastic bag with talcum powder during long periods of non-use.

5.4.2.1 Dry Suit Insulation

The amount of suit insulation needed for a particular diver to remain comfortable on a given dive is determined by water temperature, duration of the dive, and the age, body size, sex, and exercise rate of the diver. However, many suits are insulated with materials that trap air and stabilize it. The most common insulation materials in use are synthetic fibers made of polyester, nylon, and polypropylene. These fibers, used in piles, buntings, and batting, are selected because of their low water absorption.

Underwear made of such material provides primary thermal protection when divers wear a dry suit because the shell of the suit loses its insulation with depth and a diver's other outer garments have little inherent insulation. Leaks can always be a problem with shell suits; however, divers equipped with dry suits and nylon pile or Thinsulite® undergarments have been able to work intermittently for 6 hours in 2°C (35°F) water (Zumrick 1985).

5.4.2.2 Variable-Volume Neoprene or Rubber Dry Suits

Variable-volume dry suits differ from dry fabric-shell suits. They are one-piece suits that are made of closed-cell foamed neoprene or rubber compounds. These suits are designed to conserve body heat in extremely cold water for an extended period of time (Hall 1980c). Variable-volume rubber suits are light and require no surface support, which makes them ideal for use at remote locations. These suits also are simple and reliable, which greatly reduces their maintenance and repair requirements. Operations have been conducted in arctic regions using suits of this type for long-duration dives (2 hours) under ice in 28.5°F to 30°F (-1.9°C to -1.1°C) water.

Most suits are constructed of 3/16- or 1/4-inch (0.4 or 0.6 cm) closed-cell foamed neoprene and have a nylon interior and exterior lining. One style is available that is made from a rubber compound over a tricot material. All suits of this type are designed to be worn with thermal underwear, are of one-piece construction, and are entered through a water- and pressure-proof zipper. The hood and boots usually are an integral part of the suit, but the gloves are separate. To prevent separation, all seams are glued and sewn. Because the knees of the suit are the point of most frequent abuse, knee pads often are attached permanently to the suit to reduce the likelihood of leaks.

The suit may be inflated via an inlet valve connected to the diver's air supply at the low-pressure fitting on the regulator. Air inside the suit can be exhausted either by a valve on the opposite side of the chest from the inlet valve or one on the suit's arm. By manipulating these two valves, a properly weighted diver can maintain buoyancy control at any depth.

When diving in cold weather, care must be taken to avoid icing of the suit's inlet and exhaust valves. The inlet valve may be frozen in the open position if the suit is inflated with long bursts of expanding air instead of several short bursts. When the inlet valve freezes in the open position, the suit may overexpand and cause an uncontrolled ascent. If there is more air in the suit than the exhaust valve can exhaust, the diver should hold up one arm, remove his or her tight-fitting glove, and allow the excess air to escape under the suit's wrist seal.

The disadvantages of variable-volume dry suits are:

- Long suits are fatiguing because of the suit's bulk;
- Air can migrate into the foot area if the diver is horizontal or head down, causing local overinflation and loss of fins;
- Inlet and exhaust valves can malfunction; and
- A parting seam or zipper could result in sudden and drastic loss of buoyancy, as well as significant thermal stress.

Divers planning to use any type of variable-volume dry suit should be thoroughly familiar with the manufacturer's operational literature and should perform training dives under controlled conditions before wearing the suit on a working dive.

Maintaining variable-volume dry suits is relatively simple. After every use, the exterior of the suit should be washed thoroughly with fresh water, and the suit should then be inspected for punctures, tears, and seam separation, all of which must be repaired before reuse. The zipper should be closed, cleaned of any grit, and lubricated. The zipper should be coated with waterproof grease after every few uses. The inlet and outlet valves should be washed thoroughly and lubricated before and after each dive. Cuffs, collar, and face seals also require lubrication with pure silicone spray before and after each dive. The inflation hose should be inspected before each dive.

5.4.3 Hot-Water Suit Systems

Hot-water suit systems are designed to keep divers warm by encapsulating them in warm water. A hot-water system heats and closely controls the temperature of the water that is pumped through a specially insulated hose to the diver; the system then distributes the heated water evenly over the diver's body inside the passive insulation of the specially constructed suit (Figure 5-13). An open-circuit hot-water suit allows the heated water to flow back to the open sea after use, while a closed-circuit hot-water suit returns the warm water to the heater for rewarming. Hot-water systems can be used to protect more than one diver at a time and to heat a diving bell.

5.4.3.1 Open-Circuit Hot-Water Suits

Open-circuit hot-water suits are loose fitting and are made of passive insulation material; they are equipped with a control manifold and tubing to distribute warm water to the diver's arms, hands, legs, feet, and front and back torso. The suit allows used water to leak out through the suit's arm, leg, and neck seals. The control manifold must have a single valve to allow water to bypass the diver and to return directly to the surrounding water.

Figure 5-13
Open-Circuit Hot-Water Suit

Courtesy Diving Unlimited International

The hot water that supplies suits of this type may originate on the surface and be pumped directly to the diver or be passed to the diver from a diving bell, submersible, or habitat. To maintain body heat, a continuous flow of 2.5 to 3.5 gallons per minute of 95°F to 110°F (35°C to 43°C) water is required. This system does not recirculate the warm water; instead, water is dumped into the sea through the suit's vents. If the water supply is interrupted, the non-return valve retains the hot water in the suit, which allows the diver up to 18 minutes to return to the bell or surface.

5.4.3.2 Hot-Water Heater and Hoses

The heater unit of these systems contains water pumps, a heat source, and controls that deliver hot water at a prescribed temperature. The heat source may use a diesel fuel flame, electric cal-rod heaters, live steam, or a combination of these. The heat exchanger generally transfers heat from the heat source through an intermediate fresh water system to the diving water system. The intermediate system isolates the diving water system from temperature surges and reduces heater maintenance by controlling scaling and corrosion. For operational convenience, the controls that operate the heat source can be located remotely.

Hot-water suits require both a bell hose and a diver's hose. The bell hose carries hot water from the heater to the bell, and the diver's hose carries hot water either from the heater or the bell.

5.4.3.3 Closed-Circuit Hot-Water Suits

Closed-circuit hot-water suits consist of a dry suit and a special set of underwear; heated water is circulated through the underwear. Water is pumped from a heater, through a series of loops in the underwear, and back to the heat source. Hot water may originate either from a heater carried by the diver or from a surface heater. The primary advantages of closed-circuit hot-water systems are that they keep the diver dry and retain their insulating ability for some period of time if the hot-water source fails. The major disadvantages of suits of this type are that the special underwear severely restricts the diver's movement and that these suits are more fragile than the open-circuit system.

5.5 DIVER'S ACCESSORY EQUIPMENT

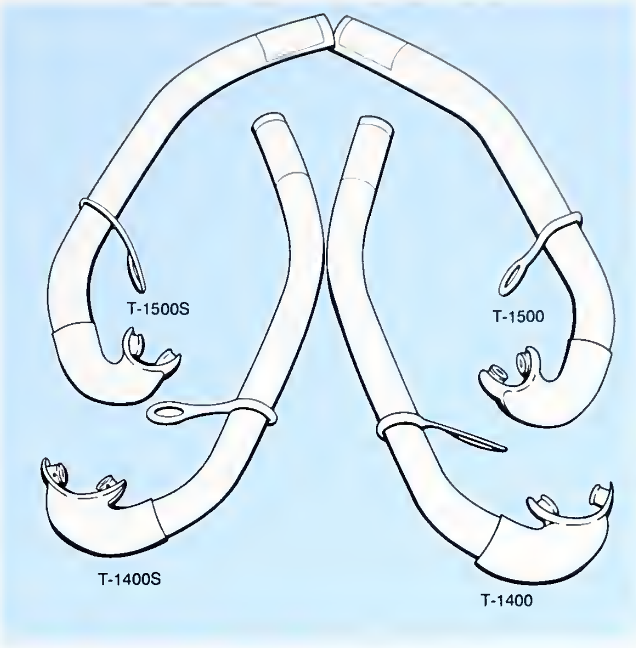
There are numerous items of accessory equipment that have special uses and are valuable to a diver to accomplish underwater tasks. The following sections describe several of these items.

5.5.1 Snorkels

A snorkel is a rubber or plastic breathing tube that allows a diver to swim comfortably on the surface without having to turn his or her head to the side to breathe. Snorkels allow scuba divers to survey the bottom in shallow water without having to carry a scuba tank.

Snorkels are available in a wide variety of designs (Figure 5-14), and selection is a matter of individual preference (Murphy 1980). The most commonly used snorkel has three segments: a barrel that protrudes above the water, a mouthpiece tube, and a mouthpiece. The mouthpiece should be selected to fit easily under the lips and should be capable of being held without excessive biting force. Soft rubber models are available, and some have a swivel feature. Other models are bent to conform to the configuration of the diver's head or to have a flexible length of hose at the breathing end that allows the mouthpiece to drop away when not in use. Although widely distributed, snorkels with a sharp bend should not be used because they increase airway resistance. Those with shallow bends, such as the wraparound models, reduce this resistance to a minimum. Snorkels with corrugated flexible tubes, however, are difficult to clear of water and additionally cause air to move in turbulent flow, which increases breathing resistance. Snorkels should have an opening of the same size at the intake as at the mouthpiece; they should not have a divider in the mouthpiece, because the divider also will cause turbulent flow.

Figure 5-14
Snorkels



Courtesy TEKNA SCUBA

Ideally, the inside diameter of the snorkel should be 5/8 to 3/4 inch (1.3 to 1.8 cm), and it should not be more than 15 inches (38.1 cm) in length. Longer snorkels increase breathing resistance, are more difficult to clear, increase dead air space, and cause additional drag when the diver is swimming under water. Snorkels flood when the diver submerges, but these devices can be cleared easily by exhaling forcefully through the tube. With some snorkels, especially those with flexible tubing near the mouthpiece, it is difficult to clear the snorkel completely, and small amounts of water may remain in the curve or corrugations of the tube. Snorkels of this type can be cleared easily when the diver surfaces.

5.5.2 Timing Devices

A **watch** is essential for determining bottom time, controlling rate of ascent, and assisting in underwater navigation; it is imperative for dives deeper than 30 feet (9 m). A diver's watch must be self-winding, pressure- and water-proof (a screw-type sealing crown is recommended), and should have a heavily constructed case that is shock-resistant and non-magnetic. An external, counter-clockwise-rotating, self-locking bezel is required for registering elapsed time. The band should be of one-piece construction and should be flexible enough to fit easily over the diver's arm. A flat, scratch-proof crystal and screw-down and lock stem also are recommended. Electronic (battery-powered) diving watches are now common, but divers should remember that batteries run down and that some of these watches are sensitive to external temperatures, which could affect their reliability during cold-water diving.

Dive timers are miniature computers that use microprocessor chips to count the number of dives in a day, the current bottom time, and the current surface interval (Figure 5-15). Some timers also can count the hours after the last dive to let the user know when it is safe to fly. Models are available that can operate for as long as 5 years without battery replacement. Dive timers are activated automatically when the diver descends to a depth below a certain depth (approximately 5 to 9 feet (1.5 to 2.7 m)). During ascent, timers stop automatically at a depth of about 3 to 5 feet (0.9 to 1.5 m).

As with other diving equipment, watches and timers must be handled with care and be washed in fresh water after they have been used in salt or chlorinated water. An important requirement for any dive timer is that it have a high-contrast face to facilitate reading under poor-visibility conditions.

5.5.3 Depth Gauges

Depth gauges (Figure 5-16) are small, portable, pressure-sensitive meters that are calibrated in feet and allow divers to determine their depth while submerged. Depth gauges are delicate instruments and must be treated carefully to avoid decalibration. Accuracy is extremely important and should be checked at regular intervals. Only a few models of depth gauges can be calibrated in the field; most models can be returned to the manufacturer if they need replacement parts. During evaluation and regular use, gauges should be checked to ensure that rough gears or internal corrosion does not cause the indicator hand to stick at particular depths.

Figure 5-15
Dive Timer

Courtesy TEKNA SCUBA

Figure 5-16
Depth Gauges

Courtesy New England Divers, Inc.

Most commercially available depth gauges operate either on the capillary, diaphragm, or bourdon tube principle. **Capillary depth gauges** consist of a plastic tube that is open to the water at one end and is attached to a display that is calibrated in feet. As depth increases, the pocket of air trapped in the tube decreases and the depth is read from the water level in the tube. The **diaphragm model** has a sealed case, one side of which is a flexible diaphragm. As pressure increases, the diaphragm is distorted, which causes the needle to which it is linked to move. **Bourdon tube depth gauges** are the most fragile of these types of gauges; they require more frequent calibration than the other types. With bourdon tubes, water pressure causes a distortion of the tube, which in turn moves a needle that indicates depth. Both bourdon tube and diaphragm depth gauges are available in models that are sealed and oil-filled for smooth, reliable operation.

Combination depth gauges are also available; these generally consist of combinations of a conventional bourdon tube with a capillary gauge around the perimeter of the face. Capillary gauges generally give more accurate readings at shallower depths, and these gauges can also be used as a reference for measuring the accuracy of a bourdon tube gauge. If the bourdon tube has been damaged, the readings provided by the two gauges at shallow depths will differ significantly.

Bourdon tube gauges tend to retain salt water in the tube, which may cause salt deposition or corrosion. To prevent this, the tube should be sucked free of water and the gauge should be stored in a jar of distilled water. Helium-filled depth gauges leak and lose accuracy if they are not kept completely submerged in water whenever they are exposed to high-pressure conditions.

Depth gauges are delicate, finely tuned instruments and must be used, stored, and maintained with great care. They are an essential part of a diver's life-support equipment, and careless handling on the part of the diver could prove fatal.

For surface-supplied divers, depth is usually measured with a **pneumofathometer**, which is a pressure gauge located on the surface. To determine a diver's depth, air is introduced into the pneumo hose at the surface. The pneumo hose is one of the members of a diver's umbilical assembly and is open to the water at the diver's end. The air introduced at the surface displaces the water in the hose and forces it out the diver's end. When the hose is clear of water, excess air escapes. The gauge connected to the hose on the surface indicates the pressure (in feet or meters of seawater equivalent) required to clear the hose of water.

5.5.4 Wrist Compass Cylinders

An **underwater compass** consists of a small magnetic compass that is housed in a waterproof and pressure-proof case and is worn attached to a diver's wrist by a band. Compasses are useful for underwater navigation, especially in conditions of reduced visibility, and they are also helpful when divers are swimming back to a boat while submerged. Compasses do not provide precise bearings, but they do provide a convenient, reliable directional reference point. To limit magnetic interference, compasses should be worn on the opposite wrist from the diver's watch and depth gauge.

Compass models are available that allow a diver to read them while holding them horizontally in front of them when swimming. Compasses do not have to be recalibrated, and the only maintenance they need is a fresh-water rinse after use.

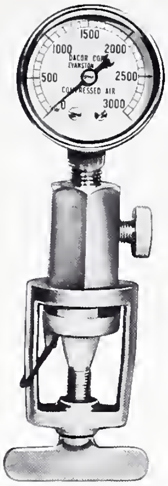
5.5.5 Pressure Gauges

Two styles of pressure gauges can be used to determine the amount of air in a scuba tank. A surface cylinder pressure gauge (Figure 5-17A) is used to check the amount of air in a tank on the surface. This type of gauge fits over the cylinder manifold outlet, attaches in the same manner as a regulator, and provides a one-time check of the pressure in a tank. A pressure-release valve is installed on the gauge so that air trapped in the gauge after the valve on a tank has been secured can be released and the gauge removed. These small dial gauge movements are designed with an accuracy of ± 100 psi, but they may become less accurate with use.

The **submersible cylinder pressure gauge** attaches directly to the first stage of a regulator by a length of high-pressure rubber hose; these gauges provide divers with a continual readout of their remaining air. Many units have a console that holds the compass, depth gauge, and tank pressure gauge (Figure 5-17B); these consoles free the diver's arms for other dive activities. Submersible pressure gauges are essential pieces of diving equipment; most of these devices operate on the same principle as the bourdon tube. One end of the submersible pressure gauge is sealed and is allowed to move; the other end is held fixed and is connected to a high-pressure air supply. As the air pressure increases, the bourdon tube tends to straighten out or to uncurl slightly. The gauge's dial face should be easy to read and should have high-contrast markings. Although gauges currently in use are designed to be accurate and reliable, they are not precision laboratory instruments. Divers should not expect accuracies better than ± 250 psig at the upper end of

Figure 5-17
Pressure Gauges

A. Cylinder Gauge



Courtesy Dacor Corporation

B. Submersible Cylinder Pressure Gauge

Courtesy TEKNA SCUBA

the gauge range and ± 100 psig at the lower end between 500 and 0 psig (Cozens 1981a).

NOTE

Submersible pressure gauges are recommended for all divers and all dives.

The only maintenance that a submersible pressure gauge needs is a fresh-water rinse after use. To prevent internal deterioration and corrosion of a surface gauge, care must be taken to ensure that the plastic plug that covers the high-pressure inlet is firmly in place. Submersible pressure gauges should be handled with care and should be stored securely when not in use.

5.5.6 Underwater Slates

A slate may be a useful piece of equipment when underwater observations are to be recorded or when divers need a means of communication beyond hand signals. A simple and useful slate can be constructed from a 1/8- or 1/4-inch (0.3 to 0.6 cm) thick piece of acrylic plastic that has been lightly sand-papered on both sides; these slates can be used with an ordinary pencil.

Semimatte plastic sheets can be placed on a clip board or in a ring binder. These sheets (about 1/32-inch (0.01 cm) thick) may be purchased in sizes up to 6 x 10 feet (1.8 to 3.0 m). They may be cut as needed, and no sanding is required. Ordinary lead pencils can be used, and marks can be erased or wiped off with a rubber eraser or an abrasive cleanser. Some underwater slates are equipped with a compass, depth gauge, and watch that are mounted across the top. When slates are used, they should be attached to the diver with a loop or lanyard made of sturdy line to keep them from being lost.

5.5.7 Diving Lights

A waterproof, pressure-proof diving light is an important item of equipment when divers are operating in areas of restricted visibility. Lights are used most frequently for photography, night diving, cave diving, wreck diving, exploring holes and crevices, or diving under ice. Regardless of the power of an underwater light, it will have only limited value in murky, dirty waters where visibility is restricted by suspended matter.

When selecting a light, there are several factors to consider, such as brightness and beam coverage, type of batteries (disposable or rechargeable), size and shape, burn time, and storage time (Figure 5-18) (Cozens 1981b). Most divers prefer the light to have a neutral or slightly positive buoyancy because it is easy to add a small weight to keep the light on the bottom, if necessary.

As with all other pieces of diving equipment, lights should be washed with fresh water after every use. The 0-ring should be lubricated with a silicone grease and should be checked for debris every time the light is assembled. When not in use, the batteries should be removed and stored separately. Before a diving light is used, it should be checked thoroughly to ensure proper operation. The batteries should be replaced any time they show any signs of running low, and spare light bulbs and batteries should be available at the dive site:

5.5.8 Signal Devices

Signal devices are an important but frequently ignored item of diving safety equipment for divers. They are

Figure 5-18
Diving Lights

particularly valuable when a diver surfaces at a great distance from the support platform or surfaces prematurely because of an emergency. Several types of signaling devices are available (Figure 5-19).

Whistles are valuable for signaling other swimmers on the surface. For easy accessibility, they may be attached to the oral inflation tube of the buoyancy vest by a short length of rubber strap.

The **military-type flare** (MK-13, Mod 0, Signal Distress, Day and Night) can be carried taped to the diver's belt or knife scabbard. One end of the flare contains a day signal, a heavy red smoke, while the opposite end holds a night signal, a red flare. Both ends are activated via a pull ring. After either end of the signal has been pulled, the flare should be held at arm's length, with the activated end pointed away from the diver at an angle of about 45 degrees. The diver's body should be positioned upwind of the signal. If the flare does not ignite immediately, waving it for a few seconds may assist ignition. After activation, the flare will work after submergence, although it will not ignite if activated under water. After every dive, the flare should be flushed with fresh water and should then be checked for damage or deterioration.

NOTE

Red flares and smoke signals should be used only as distress signals or to signal the termination of a dive.

At night, divers can carry **a flashing rescue light** that is attached to their belt, harness, or arm. Rescue lights of this type are compact, high-intensity, flashing strobe lights that are generally visible for 10 to 15 miles (16 to 24 km) from a search aircraft flying at an altitude of 1500 feet (457.2 m). These lights are waterproof and can operate submerged at depths up to 200 fsw (61 m), depending on the make and model. Some rescue lights have an operational life of as much as 9 hours; the operational life of these units can be extended greatly by using the light only intermittently.

Figure 5-19
Signal Devices

A. Diver's Pinger

Courtesy Battelle-Columbus Laboratories

B. Diver's Flasher

Courtesy Dacor Corporation

Some divers use **chemical light tubes**; these small tubes contain two separated chemicals. When the tube is bent, the chemicals discharge and mix, causing a soft green light that glows for several hours. Some divers attach these tubes to their scuba cylinders, mask straps, or snorkels as an aid to tracking their buddies, while others carry them as an emergency light source.

Signal devices should be carried so that they are easily accessible and will not be lost when equipment is discarded. Buoyancy compensators frequently have a built-in ring that will accommodate a whistle or strobe light, and flares are often taped to the scabbard of the diver's knife with friction tape.

5.5.9 Safety Lines

Diver safety lines should be used whenever divers are operating under hazardous conditions; examples of such situations are cave diving, working under ice, or diving in strong currents. Diver-to-diver lines should be used when the working conditions of the dive could separate the divers who are working under water. Safety lines provide divers with a quick and effective (although limited) means of communications. Under special conditions, a surface float can be added to the line to aid support personnel in tracking the diver.

The most commonly used types of safety line are nylon, dacron, or polypropylene. These materials are strong, have nearly neutral or slightly positive buoyancy, and are corrosion resistant. A snap can be spliced into each end of these lines to facilitate easy attachment to a float or to a diver's weight belt.

Maintenance of safety lines requires only that they be inspected and that their snaps be lubricated. Reels and lines used in cave diving must be dependable; these lines require additional maintenance and careful inspection. Any safety line should be replaced if it shows signs of weakness or abrasion.

5.5.10 Floats

A float carrying the diver's flag should be used any time a diver is operating from a beach or in an area that is frequented by small boats. Floats also provide the dive master with quick and accurate information about the diver's location and provide the diver with a point of positive buoyancy in an emergency. Floats range in size and complexity from a buoy and flag to small rafts; the type most frequently used is an automobile innertube whose center portion is lined with net. Float should be brightly colored and should carry a diver's flag positioned at the top of a staff; bright colors make the raft noticeable, and the flag tells boaters that a diver is in the water.

5.5.11 Accessories That Are Not Recommended

Several pieces of equipment are sold commercially but should not be used because they can cause injury to the diver or convert a routine situation into an emergency. **Earplugs** should never be used while diving; they create a seal at the outer ear, which prevents pressure equalization and can lead to serious ear squeeze, ruptured eardrum, and, possibly, total loss of hearing (if the plug is forced deeply into the ear cavity).

Goggles also should not be used in diving because they do not cover the nose and thus do not permit equalization of pressure. The increase in pressure inside the goggles as depth increases during the dive may cause the rim of the goggles to cut deeply into the face or the eyes to be forced against the glass plates; either of these events can cause severe and painful tissue or eye squeeze.

Regulator neckstraps should also not be worn because these straps are difficult or impossible to remove in an emergency. Some single-hose regulators come equipped with these straps as standard equipment; the straps should be removed and discarded before diving.

In addition to the specific items mentioned above, any equipment that is not necessary for the particular dive should be considered hazardous because extra equipment increases a diver's chances of fouling. Excess gear should be left on the surface.

5.6 SHARK DEFENSE DEVICES

In areas where sharks are frequent, many divers carry some form of shark defense. Several types of devices are available and have been shown to be effective. These devices are designed to be used only as defense mechanisms; they are not effective and should not be used as offensive weapons.

The oldest anti-shark device is a wooden club that is counter-weighted to facilitate underwater use and is commonly called a "shark billy." It is used to fend off or to strike a shark, preferably on the nose. Shark billies are made from 3/4-inch (1.8 cm) round fiberglass stock and are 4 feet (1.2 m) long. A hole is drilled in one end to accommodate a lanyard and a loop of surgical tubing, and the other end is ground to a point and coated with fiberglass resin. Instruments of this length and diameter can be moved through the water quickly because they afford little drag under water.

If a shark is circling a diver, the diver should use the billy to prod the shark; the butt end should be kept against the diver's body and the sharp end should be used against the shark. This defense should discourage the shark from coming closer than about 4 feet (1.2 m) from the diver. Sharks that have been prodded leave the immediate area hastily (although they return to the area almost immediately). Although brief, the shark's retreat usually provides sufficient time for the diver to leave the water (Heine 1985).

If a diver wishes to kill rather than discourage a shark, a **power head** can be used. These devices, commonly called **"bang sticks,"** consist of a specially constructed chamber designed to accommodate a powerful pistol cartridge or shotgun shell. The chamber is attached to the end of a pole and is shot or pushed against the shark, where it fires on impact. Although power heads have a built-in positive safety, they should be handled with extreme caution; they also should not be carried in water with poor visibility or at night. It also is dangerous to carry loaded power heads when several divers are working closely together in the water.

Devices known as "shark darts" are available commercially; these instruments are designed to disable or kill sharks by injecting a burst of compressed gas. Shark darts consist of a hollow stainless steel needle approximately 5 inches (12.5 cm) long that is connected to a small carbon dioxide (CO_2) cylinder or extra scuba tank; they are available in dagger or spear form (see Figure 5-20). To use these devices, the dart is thrust against the shark's abdominal cavity, where it penetrates into the animal's body cavity and discharges the contents of the CO_2 cartridge. The expanding gas creates a nearly instantaneous embolism and forces the shark toward the surface. The size of the CO_2 cylinder varies from model to model; a 12-gm cylinder is effective to a depth of 25 feet (8 m), a 16-gm cylinder to 40 feet (13 m), and a 26-gm cylinder to 100 feet (30 m). Multiple-shot compressed-air models are also available.

NOTE

In some localities, it is illegal to carry compressed-air weapons such as shark darts in automobiles or on the person. Divers are therefore advised to check with local authorities before carrying these devices.

One of the most effective methods of protecting divers in shark-infested waters is the **Shark Screen**, a lightweight synthetic bag that has three inflatable collars (Figure 5-21). In the water, the diver blows up the collars, gets into the bag, and fills it with seawater; the bag then conceals the occupant from the sea below and keeps any effusions (e.g., blood or sweat) that might attract sharks in the bag. When not in use, the bag is folded into a small package and carried in a life vest or kept with other survival gear.

5.7 UNDERWATER COMMUNICATION SYSTEMS

Several underwater communication systems have been developed and are available commercially. These systems vary in effectiveness because of their inherent deficiencies and use constraints. Studies have shown that, regardless of the efficiency of these systems, the intelligibility of messages transmitted through any type of diver communication system is less than optimal as a result of the effects of pressure, interference from the life support system, and the need for a diver to concentrate on behaviors other than communication. Message intelligibility improves significantly, however, if divers are trained to be better talkers and listeners in the underwater environment (Hollien and Rothman 1976). The four principal types of diver communication systems are described in the following sections.

Figure 5-20
Shark Darts

Photo William High

Figure 5-21
Shark Screen in Use

Photo Scott Johnson

5.7.1 Hardwire Systems

Hardwire systems employ a closed loop that is comparable to a telephone and includes a microphone, an earphone/receiver, and a cable over which the signal is transmitted. These units require a physical connection, i.e., umbilical, between the talker and the listener. Hardwire systems of the type used for surface-supplied or scuba diver communication provide the greatest degree of intelligible communication of the systems discussed here. Figure 5-22 shows the surface control panel of a hardwire diver communication system.

Most hardwire systems can be configured either for two-wire or four-wire operation. In a two-wire system, the diver usually is the priority signal path and the tender listens to the diver. If the tender wishes to talk to the diver, a switch must be thrown. The earphone and microphone on the diver's end are wired in parallel (Figure 5-23A). When two divers are operating on the same radio, the tender must push a cross-talk switch to enable the divers to talk to each other. A four-wire system (Figure 5-23B) allows the tender and divers to participate in open-line (round robin) communication, similar to that in a conference telephone call.

Most hardwire units are powered by internal 6- or 12-volt lantern-type batteries that provide continuous operation on moderate volume output for 25 hours or more. Some units feature connections for an external power supply; others incorporate redundant batteries so that a spare is always available in an emergency.

5.7.2 Acoustic Systems

The **acoustic system** includes a microphone, amplifier, power supply, and transducer; it transduces speech directly into the water by means of the projector (underwater loudspeaker). The signal produced can be received either by a hydrophone placed in the water or by divers without any special receiving equipment. Some of these systems also incorporate alarms or signals that can be used to recall divers.

5.7.3 Modulated Acoustic Systems

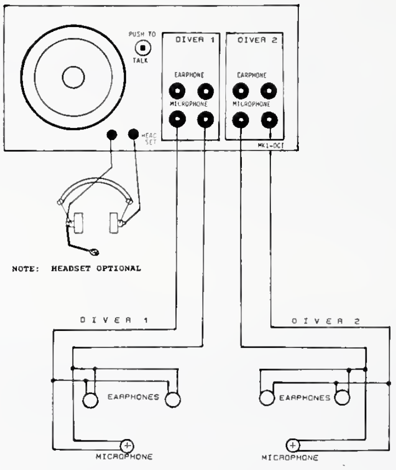
Several units of the modulated acoustic type have been manufactured, and these have performance characteristics that vary from poor to excellent. The most widely used modulated acoustic systems employ amplitude modulation (AM), a technique also used by commercial AM broadcast stations. However, since radio signals are absorbed rapidly by seawater, the acoustic carrier rather than the radio frequency carrier is modulated in diving situations. A typical system of this type consists of a microphone, power supply, amplifier, modulator, and underwater transducer (Figure 5-24). Acoustic signals produced by such systems can be

Figure 5-22
Diver Communication System

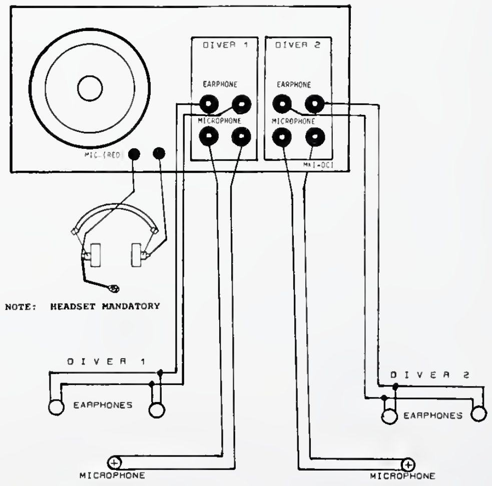
Photo Michael Pelissier, Ocean Technology Systems

Figure 5-23
Schematics of Diver Communication Systems

A. Two-Wire Mode



B. Four-Wire Mode



Courtesy Michael Pelissier, Ocean Technology Systems

Figure 5-24
Modulated Acoustic
Communication System

Photo Michael Pelissier, Ocean Technology Systems

understood only by a diver or a topside listener equipped with an appropriate receiver and demodulator. In one such unit, for example, a 31.5-kHz carrier signal is modulated by the speech signal, amplified, and projected into the water via an acoustic transducer. The acoustic signal is then picked up by another acoustic transducer, amplified, demodulated, and heard in the normal speech mode. The power output of a typical 31.5-kHz communicator is 1/2 watt. Generally, a range of 1/4 mile (0.4 km) can be expected in good ocean conditions. However, range and clarity can change dramatically because of acoustic background noise, a shadow effect (caused by the tank, buoyancy compensator, wet suit, etc.), or thermoclines.

Other modulated acoustic systems involve frequency modulation (FM) or single sideband (SSB). FM systems generally require a high ultrasonic frequency to obtain the frequency deviation necessary for intelligible communication. Generally, the higher the frequency, the greater the absorption of sound in water. As a result, few FM systems adapted to underwater use are commercially available.

Single sideband has an advantage over AM, because AM puts one-half of the total output power in the carrier, and this power is ultimately lost. SSB communicators have greater range than AM systems for the same output power and frequency. A major drawback to SSB is that it requires more complicated electronics and higher initial cost than other systems, and, as a result, most presently used underwater communication systems utilize the AM technique.

Poor intelligibility has been a problem for many users of wireless diver communications. In the late 1960's, researchers at the University of Florida sponsored a series of tests designed to elucidate this problem. During the tests, divers read phonetically balanced word lists using various masks, microphones, and communicators; test results showed intelligibility scores in the 50 percent range at best. It is now known that many human and equipment factors contribute to an increase in intelligibility. The key elements are the microphone, mask, earphone, transmitter/speech filter design, and diver training.

5.7.4 Non-acoustic Wireless Systems

Another approach to underwater communication involves a non-acoustic wireless system that uses an electric current field. Because it is non-acoustic, this system is not affected by thermoclines, natural or man-made barriers, or reverberation. Range is determined by the amount of power applied to the field platers and by the separation between them. Separation generally is limited to the diver's height, and power output is limited by what the diver can tolerate because the diver "feels" a mild shock when transmitting. This mode is limited, at best, to a range of a few hundred feet or meters. With modification, this system can be used to transmit physiological data.

SECTION 6
HYPERBARIC CHAMBERS AND SUPPORT EQUIPMENT

HYPERBARIC CHAMBERS AND SUPPORT EQUIPMENT

6

6.0 GENERAL

Hyperbaric chambers were developed to permit human beings to be subjected to an increased pressure environment. Such chambers are vessels capable of accommodating one or more occupants and of being pressurized so that the environment inside the chamber simulates water depth while the pressure outside the chamber remains at normal (1 atmosphere) pressure. Hyperbaric chambers are used in research on the effects of pressure, in the treatment of pressure-related conditions, and in the decompression of divers. For example, hyperbaric chambers are used in several situations that occur in diving: surface decompression; omitted decompression; treatment of diving accidents such as gas embolism and decompression sickness; and pressure and oxygen tolerance tests. Terms used interchangeably to denote these chambers include recompression, compression, or hyperbaric chambers (these three terms generally describe chambers used primarily to treat diving casualties), and decompression chambers (a term used to indicate that their primary use is for the surface decompression of divers). Engineers refer to these as PVHO's (Pressure Vessels for Human Occupancy).

6.1 HYPERBARIC CHAMBERS

Early models of hyperbaric chambers were single-compartment (single-lock) chambers that allowed one patient and a tender to enter and be pressurized. NOAA does not recommend the use of single-lock chambers because they do not allow medical and tending personnel to have access to the patient during treatment. All modern chambers are of the multilock type (see Figure 6-1). The multilock chamber has two or more compartments that are capable of being pressurized independently; this feature allows medical personnel and

Figure 6-1A
Double-Lock Hyperbaric Chamber—Exterior View

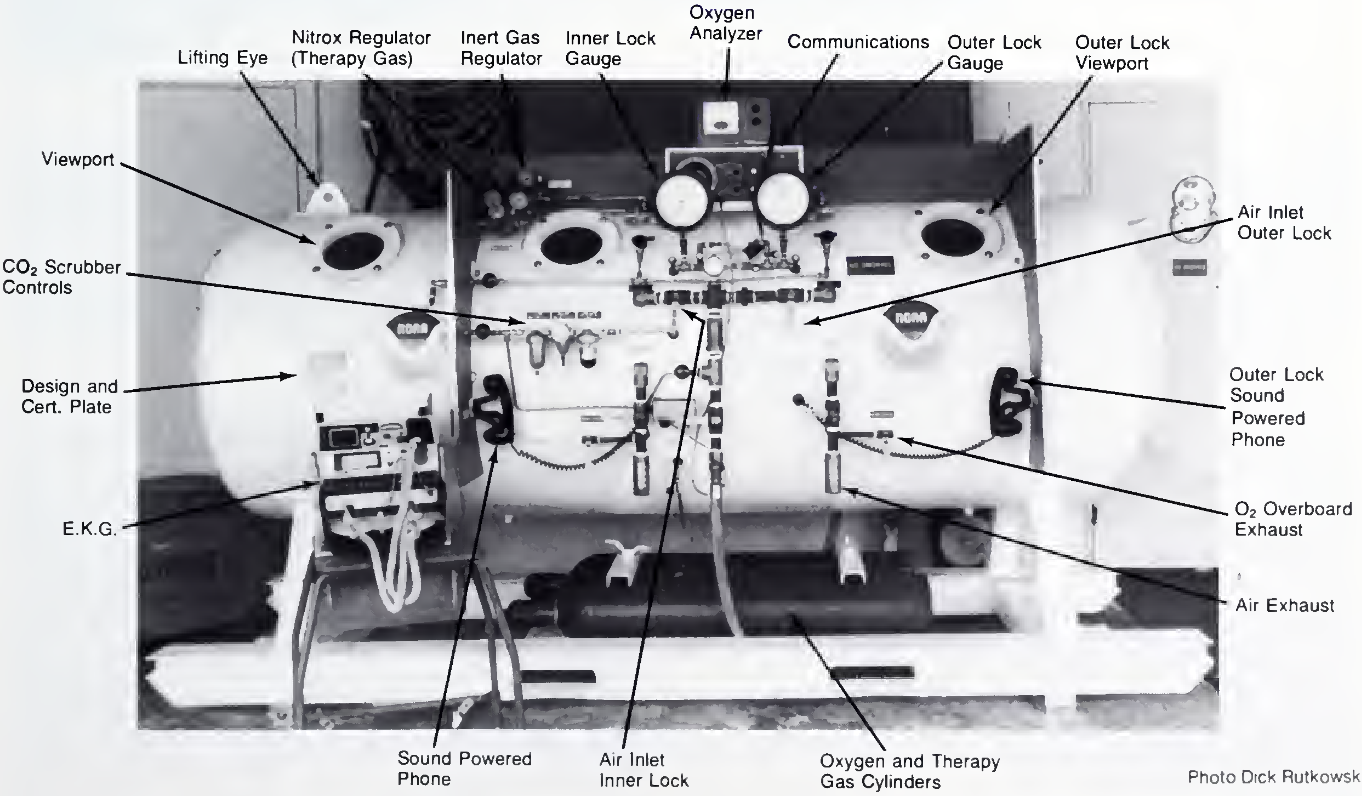


Photo Dick Rutkowski

Figure 6-1B
Double-Lock Hyperbaric Chamber—Interior View

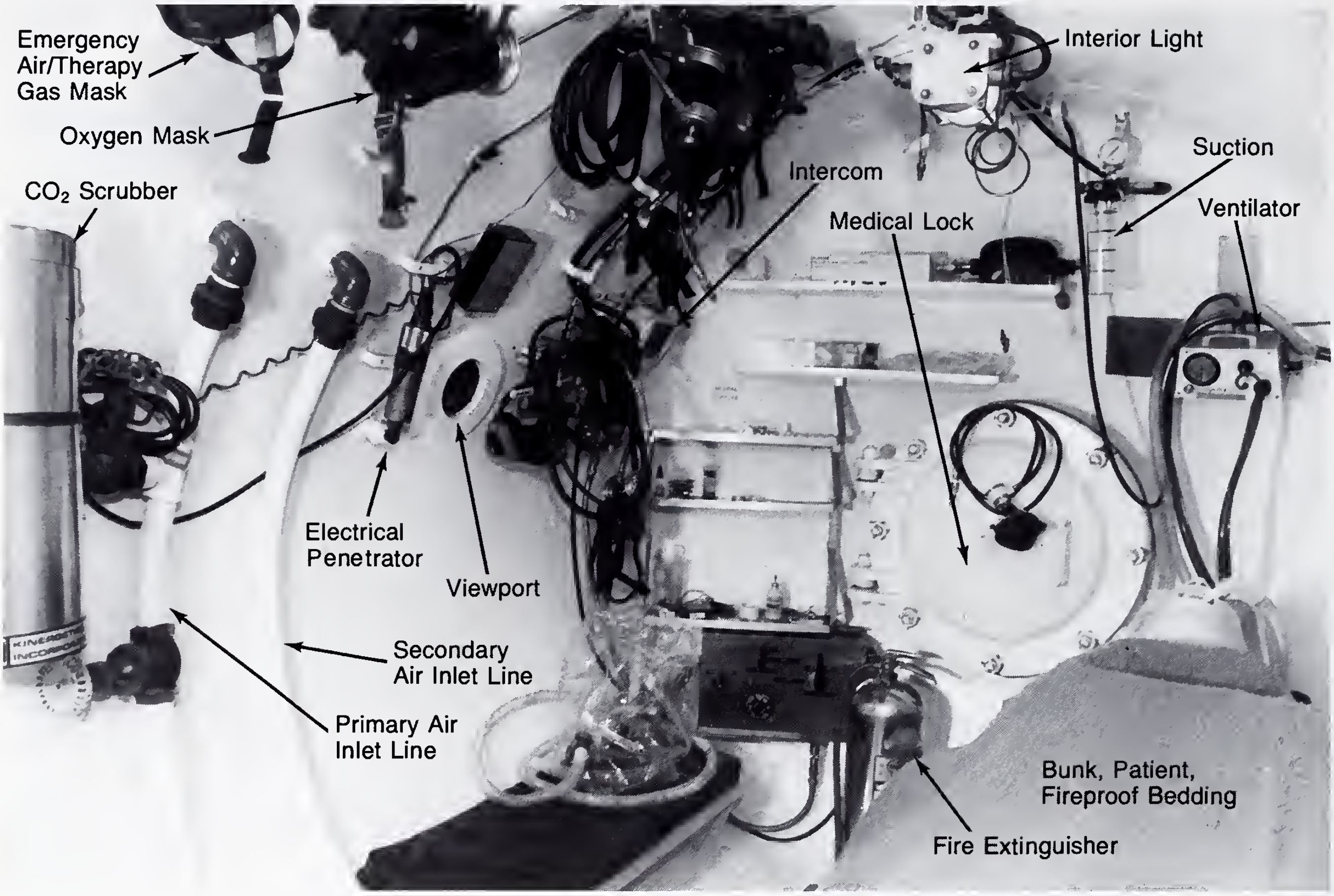


Photo Dick Rutkowski

tenders to enter the chamber to treat the patient and then to leave, while the patient remains at the desired pressure in the inner compartment.

A chamber should be equipped with the following:

- A two-way communication system
- A mask breathing system for oxygen (normally of the demand type, although ventilation hoods are gaining acceptance for clinical treatment) (Figure 6-2)
- Emergency air/mixed gas breathing masks
- Pressurization and exhaust systems
- A fire extinguishing system
- External lighting that illuminates the interior
- Viewports
- Depth control gauges and control manifolds
- Heating and air conditioning systems (highly desirable)
- Stop watches (elapsed time with hour, minute, and second hands)
- Gas sampling ports.

Multiplace chambers are designed to accommodate several occupants at the same time. Deck decompression chambers (located on the deck of the surface platform or support ship) and land-based chambers used for recompression treatment and diving research or for clinical hyperbaric treatment and research are examples of multiplace chambers.

6.1.1 Transportable Chambers

Small portable chambers, varying in size and shape from single-person, folding chambers made from modern lightweight materials (Figure 6-3) to L-shaped, two-person capsules, have been used in emergencies to recompress divers being transported to a large well-equipped chamber. Transportable chambers are most valuable when they are of the two-person type and are capable of being mated to a larger chamber, because these features allow the patient to be continuously tended and pressurized. Small one-person transportable

Figure 6-2
Mask Breathing System for Use in Hyperbaric Chamber

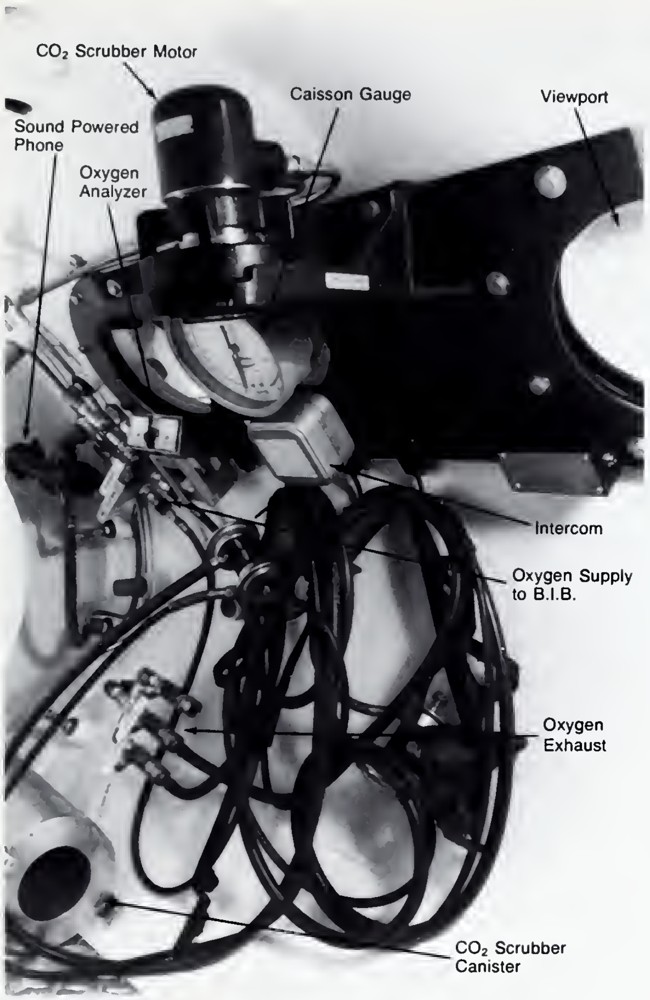


Photo Dick Rutkowski

chambers, although better than no recompression capability at all, have major shortcomings because an attendant outside the chamber has no way to perform lifesaving measures, such as maintaining an airway, performing cardiopulmonary resuscitation, or relieving a pneumothorax.

6.2 DESIGN AND CERTIFICATION

Several codes and standards apply to man-rated pressure vessels, including current standards set by the American National Standards Institute, the American Society of Mechanical Engineers, the National Fire Protection Association, and, under certain circumstances, the U.S. Coast Guard. These codes are comprehensive where the structural integrity of the vessel is concerned and include all aspects of material selection, welding, penetrations into the pressure vessel walls, flanges for entry or exit, and testing. Only high-quality pressure gauges and ancillary equipment should be used in outfitting a hyperbaric chamber. All such equipment should be tested and calibrated before a diving operation. Figure 6-4 is an example of a certification plate and shows various specifications and certifications.

NOTE

If structural modifications such as those involving welding or drilling are made, the chamber must be recertified before further use.

Hyperbaric chambers used in diving usually are cylindrical steel pressure vessels that are designed to withstand an internal working pressure of at least 6 atmospheres absolute (ATA) (165 fsw). Modern chambers generally are 54-60 inches (137-152 centimeters) in inside diameter but may have inside diameters ranging from 30 inches (76 centimeters) to as large as 10 feet (3 meters). Large chambers used to house and decompress divers for long saturation exposures are outfitted with toilet facilities, beds, and showers, but such comfortable chambers usually are found only at sites where large-scale diving operations or experimental dives are conducted.

6.3 OPERATION

6.3.1 Predive Checklist

A predive check of each chamber must be conducted before operation. If pressurized by a compressor, the gas source must be checked to see that the intake is clean and will not pick up exhaust from toxic sources. The predive checklist (see Table 6-1) should be posted on the chamber itself or on a clipboard next to the chamber.

6.3.2 Gas Supply

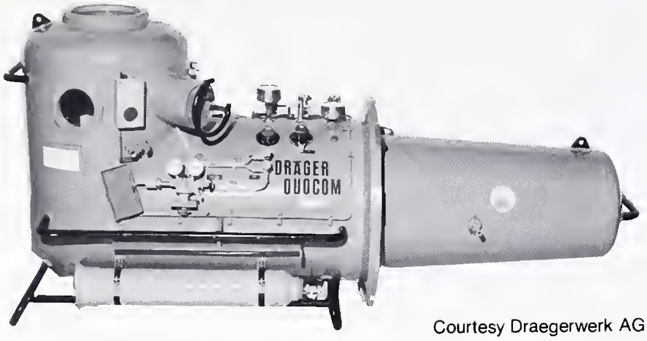
A chamber treatment facility should have a primary and a secondary air supply that will satisfy the following requirements:

Primary supply—sufficient air to pressurize the chamber twice to 165 fsw and to ventilate throughout the treatment;

Secondary supply—sufficient air to pressurize the chamber once to 165 fsw and to ventilate for 1 hour.

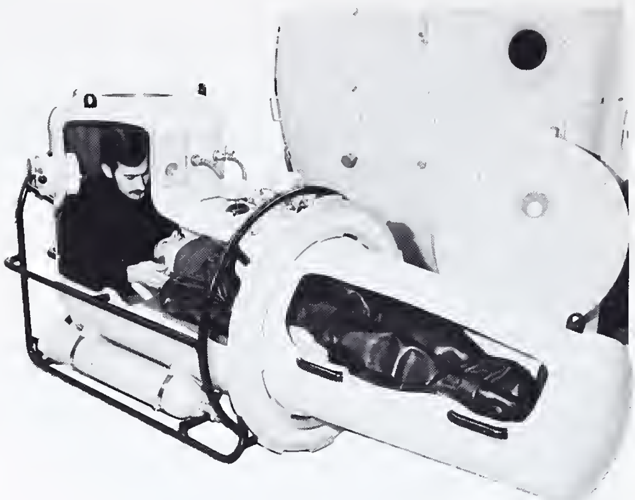
Figure 6-3
Transportable Chambers

A. Total system



Courtesy Draegerwerk AG

B. Schematic showing victim and tender



Courtesy Draegerwerk AG

C. Lightweight one-person transportable chamber

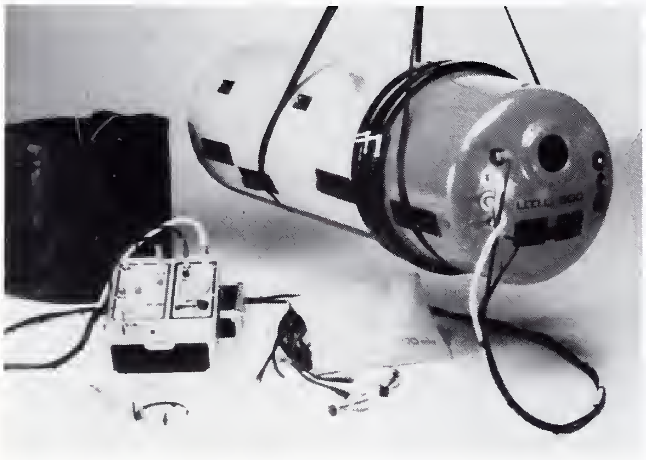
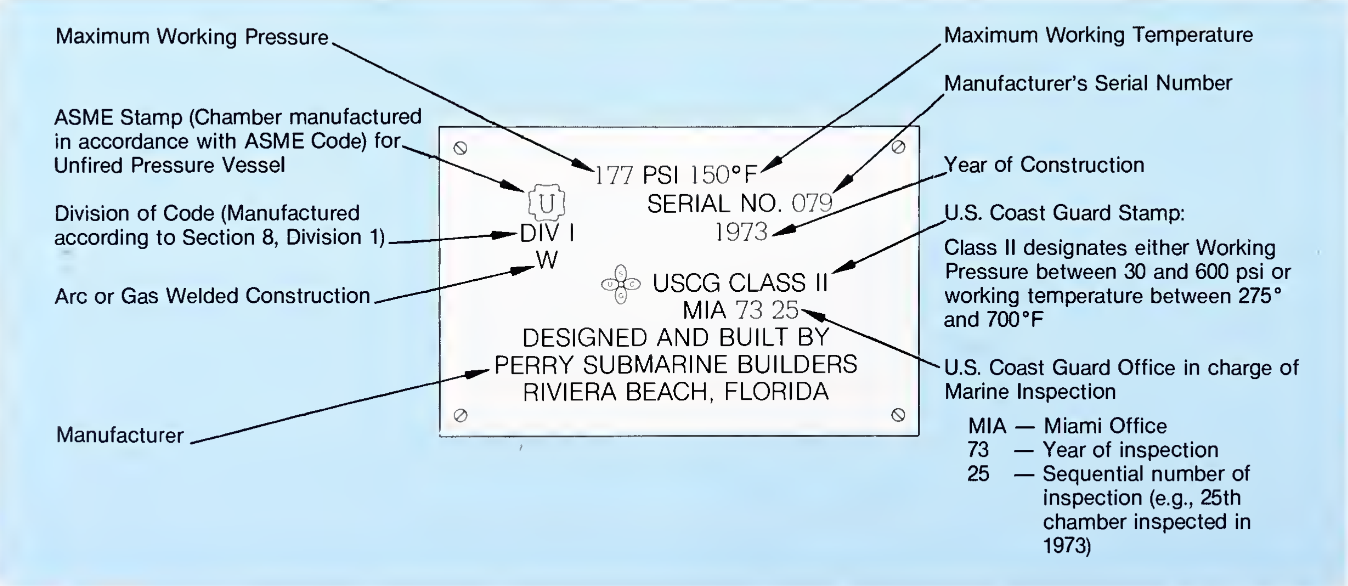


Photo Butch Hendrick

Technical Data:

Max. operating pressure:	5 bar	— 72.5 pounds/sq. in.
Test pressure:	7.5 bar	— 108.75 pounds/sq. in.
Total volume:	700 liters	— 42,714 cu. in.
Total outside length:	2540 mm	— 100.00 in.
Total outside height:	1520 mm	— 59.84 in.
Total outside width:	860 mm	— 33.86 in.
Outside height (without mobile base):	1200 mm	— 47.24 in.
Total inside length:	2350 mm	— 92.52 in.
Largest inside diameter:	640 mm	— 25.20 in.
Total weight:	approx. 500 kp	— 1102.5 pounds
Weight of the complete base:	approx. 275 kp	— 606.4 pounds
Weight of the complete pressure chamber without base:	approx. 225 kp	— 496.1 pounds
Acceptance:	Techn. Inspect. Agency (TÜV)	

Figure 6-4
Certification Plate for Hyperbaric Chamber



Source: NOAA (1979)

Table 6-1
Hyperbaric Chamber Predive Checkout Procedures

Before every operation of the chamber, a predive check of the facility must be conducted. This procedure should take only a few minutes, provided that the personnel are experienced and the chamber is properly maintained.

Predive Checklist

CHAMBER
____ Clean
____ Free of all extraneous equipment
____ Free of noxious odors
____ Doors and seals undamaged, seals lubricated
____ Pressure gauges calibrated, compared.

AIR SUPPLY SYSTEM
Primary air supply adequate for two pressurizations to
____ 165 feet plus ventilation
Secondary air supply adequate for one pressurization
____ and 1 hour of ventilation
____ Supply valve closed
____ Equalization valve closed
Supply regulator set at 350 psig or 250 psig, depending
____ on working pressure (200 or 100 psi) of chamber
____ Fittings tight, filters clean, compressors fueled.

OXYGEN SUPPLY SYSTEM
Cylinders full; marked as BREATHING OXYGEN;
____ cylinder valves open
____ Replacement cylinders on hand
____ Inhalators installed and functioning
____ Regulator set between 75 and 100 psig
____ Fittings tight, gauges calibrated
____ Oxygen manifold valves closed.

NITROX (Therapy Gas)
Cylinders full; marked 60% N_2/40% O_2;
____ cylinder valves open
____ Replacement cylinders on hand
____ Inhalators installed and functioning
____ Regulator set between 75 and 100 psig
____ Fittings tight, gauges calibrated
____ NITROX valves closed.

ELECTRICAL SYSTEM
____ Lights operational
____ Wiring approved, properly grounded
Monitoring equipment (if applicable)
____ calibrated and operational.

COMMUNICATION SYSTEM
____ Primary system operational
____ Secondary system operational.

FIRE PREVENTION SYSTEM
Water and appropriate fire extinguisher in chamber. For chambers with installed fire suppression system,
____ pressure on tank
____ Combustible material in metal enclosure
____ Fire-resistant clothing worn by all chamber occupants
____ Fire-resistant mattress and blankets in chamber.

MISCELLANEOUS—INSIDE CHAMBER
____ Slate, chalk, and mallet
____ Bucket and plastic bags for body waste
____ Primary medical kit
Ear protection sound attenuators/aural protectors
____ (one pair per occupant).

MISCELLANEOUS—OUTSIDE CHAMBER
____ Stopwatches
____ Recompression treatment time
____ Decompression time-personnel leaving chamber
____ Cumulative time
____ Spare
____ U.S. Navy recompression treatment tables
____ U.S. Navy decompression tables
____ Log
____ List of emergency procedures
____ Secondary medical kit
____ Oxygen analyzers functioning and calibrated.

CLOSED-CIRCUIT OPERATIONS (WHEN APPLICABLE)
____ CO_2 scrubber functional
____ Adequate CO_2 absorbent
____ CO_2 analyzer functional.

Both the primary and secondary supply may be provided by any combination of stored and compressor capacities that will provide the required amounts of air at the appropriate pressure in the required times.

If it is not feasible to have a high-pressure system available as a backup, two low-pressure systems may be used. In addition to having an adequate volume of stored gas, it is important to be aware of the possibility of power failures and, wherever possible, to keep an emergency generator available to provide continuous power if service is interrupted. Personnel at chamber installations should be familiar with local fire and rescue units that can provide emergency power and air.

The compressor should have a card in a conspicuous place showing the date of service and type of lubricant used. Before activating a hyperbaric chamber, the operator must ensure that the predive checklist shown in Table 6-1 has been completed.

WARNING

Compressors Should Be Lubricated With Lubricants That Will Not Break Down Under Heat or High Pressure, and Filters Should Be Changed According to Required Maintenance Procedures

6.3.3 Chamber Ventilation and Calculation of Gas Supply

Unless the chamber is equipped with a scrubber, it is necessary to ventilate the chamber with fresh air to maintain safe levels of carbon dioxide and oxygen inside the chamber. The rate at which air must be circulated through the chamber depends on the number of personnel inside the chamber, their level of activity, the chamber depth, and the breathing gas being used.

NOTE

The abbreviation acfm refers to actual cubic feet per minute at the chamber pressure in use at the time; scfm refers to standard cubic feet per minute, defined as cubic feet per minute at standard conditions at one atmosphere pressure and 0° C [acfm = (scfm)/(chamber pressure in atmospheres absolute, usually expressed as (D + 33)/33), where D = chamber depth in fsw].

The following procedures reflect various scenarios encountered in chamber operations:

(1) When occupants are breathing air in the chamber:
  (a) 2 acfm for each person at rest
  (b) 4 acfm for each person not at rest.
(2) When occupants are breathing oxygen by mask in a chamber without an overboard dump system:
  (a) 12.5 acfm for each person at rest
  (b) 25.0 acfm for each person not at rest
  (c) Additional ventilation is not necessary for occupants who are not breathing oxygen.
(3) Interrupted ventilation:
  (a) Should not exceed 5 minutes during any 30-minute period.
  (b) When resumed, should use twice the required acfm for twice the period of interruption, and then the normal rate should be resumed.
(4) When oxygen monitoring equipment is available:
  (a) Ventilation should be used as required to maintain oxygen concentration in the chamber below 23 percent.
(5) With an installed overboard dump system:
  (a) The ventilation rates for air breathing given in Step 1 above should be used.

The quantity of air ventilated through the chamber is controlled by regulating the precalibrated exhaust valve outside the chamber. Once the exhaust rate has been established, the air supply valve can be regulated to maintain a constant chamber pressure.

The chamber air supply should be maintained at a minimum supply pressure of 100 psig over maximum chamber pressure. Regulator settings for oxygen depend on the type of oxygen breathing masks installed in the chamber; most masks should be supplied with gas at between 75 and 100 psig above the chamber pressure.

Knowing the amount of air that must be used does not solve the ventilation problem unless there is some way to determine the volume of air actually being used for ventilation. The standard procedure is to open the exhaust valve a given number of turns (or fractions of a turn), which provides a certain number of actual cubic feet of ventilation per minute at a specific chamber pressure, and to use the air supply valve to maintain a constant chamber pressure during the ventilation period.

- The exhaust valve handle should be marked so that it is possible to determine accurately the number of turns and fractions of turns.
- The rules in this paragraph should be checked against probable situations to determine the rates of ventilation at various depths (chamber pressures) that are likely to be needed. If the air supply is ample, determination of ventilation rates for a few depths (30, 60, 100, 165 fsw) may be sufficient, because the valve opening specified for a given rate of flow at one depth normally will provide at least that much flow at a deeper depth.
- The necessary valve settings for the selected flows and depths should be determined with the help of a stopwatch by using the chamber itself as a measuring vessel.
- The ventilation rate can be calculated by using this formula:

$$R = \frac{V \times 18}{t \times \frac{(P + 33)}{33}}$$

where

R = chamber ventilation rate in acfm;

V = volume of chamber in cubic feet;

t = time for chamber pressure to change 10 fsw in seconds;

P = chamber pressure (gauge) in fsw.

Chamber pressure in the unoccupied chamber should be increased to 5 fsw beyond the depth in question. The exhaust valve should then be opened a certain amount and the length of time it takes to come up to 10 fsw below this maximum depth should be determined. (For example, if checking for a depth of 165 fsw, the chamber pressure should be taken to 170 fsw and the time it takes to reach 160 fsw should be measured.) The valve should be opened different degrees until the setting that approximates the desired time is known; that setting should then be written down. Times for other rates and depths should be calculated and settings determined for these in the same way. A chart or table of the valve settings should be made and a ventilation chart using this information and the ventilation rates should be prepared.

Primary system capacity (for a chamber not equipped with a mask overboard discharge system and assuming there are two patients and one tender in the chamber) is calculated as follows:

$$Cp = 10V + 48{,}502$$

where

Cp = total capacity of primary system (scf);

V = chamber volume (ft^3);

10 = atmospheres needed to pressurize twice from the surface to 165 fsw;

48,502 = total air (in scf) required to ventilate during a treatment using USN Treatment Table 4.

Table 6-2 shows ventilation rates and total air requirements for two patients and one attendant undergoing recompression treatment (US Navy 1985). As indicated, the maximum air flow rate that the system must deliver is 70.4 scfm (with an oxygen stop at 60 fsw).

Secondary System Capacity

To calculate secondary system capacity, the formula is

$$Cs = 5V + 4{,}224$$

where

Cs = total capacity of secondary system (scf);

V = chamber volume (ft^3);

5 = atmospheres required to pressurize from the surface to 165 feet once;

4,224 = maximum ventilation rate of 70.5 scfm for 1 hour.

The exhaust intake must be placed inside the chamber as far away from the supply inlet as practical to ensure maximum circulation within the chamber and to prevent fresh air from being drawn from the chamber during ventilations.

6.3.4 Mask Breathing System

The oxygen system provides oxygen for that part of the decompression/recompression schedule requiring pure oxygen. It also provides a source of known clean air in the event of fouling of the air in the chamber. The system should be inspected carefully and checked for leaks. Smoking in the vicinity of a chamber is prohibited.

A hyperbaric chamber may be equipped with both standard and overboard discharge breathing masks. The standard mask is generally used with air but can be used with mixed gas or treatment gas. Overboard discharge masks are generally used for oxygen breathing during recompression or treatments. The standard breathing mask consists of an oral-nasal mask, demand regulator for oxygen or air supply, appropriate hoses and fittings, and an in-board dump (or discharge) system (see Figure 6-2). A breathing mask with an overboard discharge system consists of the same basic components as the standard mask, with the addition of a mask-mounted demand exhaust regulator and appropriate hoses and fittings to exhaust the diver's exhaled breath outside the recompression chamber; overboard dump systems are usually used for oxygen breathing.

The oxygen cylinder pressure is reduced to approximately 75 psig over chamber pressure by a pressure regulator. This pressure differential is maintained by a suitable tracking regulator or by operator manipulation of a standard regulator as required by changes in chamber depth. The resulting low-pressure oxygen or air flows through a lightweight, flexible hose to a demand regulator located on the mask. A control knob on the demand regulator allows adjustment of the regulator to minimize breathing resistance or to permit constant flow, if this is desired. The gas delivery pressure also may be adjusted from outside the chamber to enhance flow characteristics.

With the overboard discharge units, the diver's exhalation is removed through a regulator that is mounted on the side of the mask. The regulator exhaust is connected by a hose to the outside of the chamber. For a pressure differential in excess of 60 fsw, an auxiliary regulator must be connected between the hose and the chamber wall to limit the differential pressure at the outlet of the mask-mounted regulator. The unit should not be pressurized to a depth greater than 60 fsw unless it is fitted with an auxiliary vacuum regulator or the

Table 6-2
Ventilation Rates and Total Air Requirements for Two Patients and One Tender Undergoing Recompression Treatment

Depth of Stop (fsw)	Ventilation Rate (scfm)		Ventilation Air Required at Stop (scf) Treatment Table							Using O_2 from 60'
	Air Stop	O_2 Stop	5	6	6A	1A	2A	3	4	4
165	47.9				1437		1437	1437	5749	5749
140	41.9						503	503	1256	1256
120	37				139		444	444	1111	1111
100	32.2					966	386	386	966	966
80	27.3					328	328	328	821	821
60	22.5	70.4	2929	4561	4561	675	675	675	8104	25344
50	20.1	62.9				603	603	603	7234	22644
40	17.7	55.3	1772	1772	1772	530	530	530	6363	19908
30	15.3	47.7	1107	6183	6183	916	1831	10996	10996	34344
20	12.8	40.2				770	1540	1540	1540	7236
10	10.4	32.6	1090	1090	1090	1250	2501	1250	1250	5868
Total for Ventilation			6898	13606	15182	6038	10778	18692	45390	125247

NOTE: Total air requirements are dependent on chamber size.

Depth of Stop	Duration	Air Required
60'	4 Hr. O_2	16,903
	4 Hr. Air	5,400
	4 Hr. O_2	16,903
60'	4 Hr. Air	3,672
to	4 Hr. O_2	14,430
30'	2 Hr. Air	1,922
30'	2 Hr. Air	1,776
to	4 Hr. O_2	10,012
10'	4 Hr. Air	2,726
10'	4 Hr. O_2	6,262
to	2 Hr. Air	624
4'		
at 4'	2 Hr. Air	499
	2 Hr. O_2	1,563
4'	4 Min.	26
to Surface		82,718 (min)

Adapted from US Navy (1985)

discharge hose has been disconnected from the external port.

These units should be inspected by the inside tender or supervisor before each use. Hose fittings should be inserted into properly labeled connectors on the wall of the chamber. After testing, the internal and external valves should be closed until mask breathing gas is required.

The mask must be cleaned with an antiseptic solution (antibacterial soap and warm water, alcohol, and sterilizing agent) after each use, air-dried, and stored in a sealed plastic bag or be reinstalled for subsequent use. Routine inspection and preventive maintenance are required annually or when malfunctioning is evident. Generally, inspection and repair service is provided by the manufacturer. For further information, consult the appropriate manufacturer's instruction manual (see the predive checklist in Table 6-1).

6.3.5 Oxygen Analyzers

An oxygen analyzer is useful for monitoring oxygen concentrations in chambers where oxygen is used for therapy, surface decompression, or research. The oxygen level in a hyperbaric chamber should be maintained between 21 and 23 percent to reduce the danger of fire (see Section 6.5). An absolute upper limit of 25 percent should be observed, in accordance with current National Fire Protection Association rules.

Several oxygen analyzers are available. For units placed outside the chamber with a remote sensor located

Table 6-3
Chamber Post-Dive Maintenance Checklist

AIR SUPPLY
____ Close all valves
____ Recharge, gauge, and record pressure of air banks
____ Fuel compressors
____ Clean compressors according to manufacturer's technical manual.

VIEWPORTS AND DOORS
____ Check viewports for damage; replace as necessary
____ Check door seals; replace as necessary
____ Lubricate door seals with approved lubricant.

CHAMBER
____ Wipe inside clean with vegetable-base soap and warm fresh water
____ Remove all but necessary support items from chamber
____ Clean and replace blankets
____ Encase all flammable material in chamber in fire-resistant containers
____ Restock primary medical kit as required
____ Empty, wash, and sanitize human waste bucket
____ Check presence of sand and water buckets in chamber
____ Air out chamber
____ Close (do not seal) outer door. Preferably leave one light on inside chamber to keep moisture out.

SUPPORT ITEMS
____ Check and reset stopwatches and lock them in control desk drawer
____ Ensure presence of decompression and treatment tables, list of emergency and ventilation procedures, and the *NOAA Diving Manual*
____ Restock secondary medical kit as required and stow
____ Clean and stow fire-retardant clothing
____ Check that all log entries have been made
____ Stow log book.

OXYGEN SUPPLY
____ Check inhalators, replace as necessary
____ Close O_2 cylinder valves
____ Bleed O_2 system
____ Close all valves
____ Replace cylinders with BREATHING OXYGEN, as required
____ Ensure spare cylinders are available
____ Clean system if contamination is suspected.

NITROX (Therapy Gas) SUPPLY
____ Check inhalators, replace as necessary
____ Close NITROX cylinder valves
____ Bleed NITROX system
____ Close all valves
____ Replace cylinders with 60% N_2/40% O_2, as required
____ Ensure spare cylinders available.

COMMUNICATIONS
____ Test primary and secondary systems; make repairs as necessary.

ELECTRICAL
____ Check all circuits
____ Replace light bulbs as necessary
____ If lights encased in pressure-proof housing, check housing for damage
____ Turn off all power
____ Check wiring for fraying
____ If environmental monitoring equipment is used, maintain in accordance with applicable technical manual.

inside the chamber, an appropriate chamber penetration is required. Small, portable, galvanic cell-type units, however, may be placed directly in the chamber. When choosing portable units for hyperbaric use, the manufacturer's instructions should be consulted to be certain that the unit is compatible with hyperbaric environments. Since nearly all units read out in response to partial pressures of oxygen relative to a pressure of 1 ATA, mathematical conversions must be made to ascertain the true reading at depth. The manufacturer's instructions should be consulted for detailed information on specific oxygen analyzers.

6.3.6 Electrical System

The electrical system in a chamber varies in complexity, depending on the capability and size of the chamber. Whenever possible, it is best to keep all electricity out of the chamber, to provide lights through fiber optics or through port windows, and to have the actual electrical system controls located outside the chamber. When chambers have electrical systems and lights inside, they must be inspected to ensure that the system is properly grounded and that all fittings and terminals are in good order and encased in spark-proof housings (see the predive checklist in Table 6-1).

WARNING

Lights Inside the Chamber Must Never Be Covered With Clothing, Blankets, or Other Articles That Might Heat Up and Ignite

6.4 CHAMBER MAINTENANCE

Proper care of a hyperbaric chamber requires both routine and periodic maintenance. After every use or no less than once a month, whichever comes first, the chamber should be maintained routinely in accordance with the Post-Dive Maintenance Checklist shown in Table 6-3. At this time, minor repairs should be made and supplies restocked. At least twice a year, the chamber should be inspected both outside and inside. Any deposits of grease, dust, or other dirt should be removed and the affected areas repainted (steel chambers only).

Only steel chambers are painted. Aluminum chambers normally are a dull, uneven gray color that permits corrosion to be recognized easily. Painting an aluminum chamber will serve only to hide (and thus encourage) corrosion. Corrosion is best removed by hand-sanding or by using a slender pointed tool, being careful not to gouge or otherwise damage the base metal. The corroded area and a small area around it should be cleaned to remove any remaining paint or corrosion products. Steel chambers should then be painted with a non-toxic, flame-retardant paint.

All NOAA hyperbaric chambers must be pressure tested at prescribed intervals. The procedures to be followed are shown in Table 6-4, and Table 6-5 presents a checklist for chamber pressure and leak tests.

6.5 FIRE PREVENTION

A hyperbaric chamber poses a special fire hazard because of the increased flammability of materials in compressed air or an environment otherwise enriched in oxygen. Fire safety in hyperbaric chambers requires basically the same practices as it does in other locations. The chamber environment, however, involves two special considerations—the atmosphere is an "artificial" one, and people are confined with the fire in a relatively small space. The traditional trio of conditions necessary for a fire, in a chamber or anywhere else, are a source of ignition, combustible materials, and an oxidizer. There are four steps in chamber fire safety in addition to preventive measures: detecting the fire, extinguishing it, using a mask for breathing, and—if possible—escaping.

A safe chamber begins in the design stage. Various codes and design handbooks deal with this complex subject, and it can only be touched on here (Naval Facilities Engineering Command 1972, National Fire Protection Association 1984). After safe design, the manner in which the chamber is used is next in importance. This section reviews chamber fire safety, covering both basic principles and operational techniques. For a more thorough treatment of the subject and additional references, consult the section on fire safety in *The Underwater Handbook* (Shilling, Werts, and Schandelmeier 1976, pp. 646-664).

6.5.1 Ignition

Possible sources of ignition in a hyperbaric chamber include:

- Electrical wiring or apparatus
- Cigarettes or other smoking materials
- Heat of compression
- Electrostatic sparks.

The most common sources of chamber fires in the past have been lighted cigarettes, faulty electrical wiring, and sparks from electrically powered devices. Electrical fires, however, can start either from overheating caused by a defective component, a short circuit, a jammed rotor in a motor, sparks produced by making or breaking a load-carrying circuit, or from a device with arcing brushes.

The safe use of electrical devices in a chamber is primarily a design factor, requiring proper installation of the supply wiring and properly designed devices. Wiring should be insulated with mineral materials or Teflon® and be shielded in metal conduit (which can be either rigid or flexible). The housings of electrical devices such as instruments can be purged with an oxygen-free inert gas during operation and may or may not be pressure proof. Lights may be enclosed and purged, or they may be external to the chamber and have the light directed inside with a "light pipe" or fiber optic cable. Even an enclosed light can generate enough heat to start a fire, a fact to be considered at both the design and operational stages. A fire protection plan should include the capability to disconnect all electrical power instantaneously. Auxiliary lighting must be available.

At some installations, control of the electrical hazard is achieved by allowing no electricity in the chamber at all. When electricity is used, however, it requires protection of the occupants from electrical shocks. This may be accomplished by employing protective devices such as ground fault detectors and interrupters. Use of low voltages (e.g., 12 or 24 volts) avoids this hazard, but it is a dangerous misunderstanding to think such voltages cannot start a fire if high-current flow is possible. Devices tolerant of pressure and qualifying as intrinsically safe may be used. Low-current, low-voltage devices such as headsets and microphones generally are considered safe. There is a fundamental difference between the concepts behind "explosion-proof" devices and those required for chamber safety. Explosion-proof housings are made to prevent the ignition of flammable gases or vapors by sparks generated by electrical equipment; this is not the expected problem in a diving chamber. Junction boxes and other equipment made to explosion-proof standards may provide the kind of protection afforded by mechanical housings (mentioned above), but this equipment is designed for a purpose different from the enriched-oxygen hyperbaric environment and may in fact be inadequate. Also, most explosion-proof boxes are much

Table 6-4
Pressure Test Procedures for NOAA Chambers*

A pressure test must be conducted on every NOAA recompression chamber:

1. When initially installed;
2. When moved and reinstalled;
3. At 2-year intervals when in place at a given location.

The test is to be conducted as follows:

1. Pressurize the innermost lock to 100 feet (45 psig). Using soapy water or an equivalent solution, leak test all shell penetration fittings, viewports, dog seals, door dogs (where applicable), valve connections, pipe joints, and shell weldments.
2. Mark all leaks. Depressurize the lock and adjust, repair, or replace components as necessary to eliminate leaks.
    a. Viewport Leaks - Remove the viewport gasket (replace if necessary), wipe.

CAUTION

Acrylic viewports should not be lubricated or come in contact with any lubricant. Acrylic viewports should not come in contact with any volatile detergent or leak detector (non-ionic detergent is to be used for leak test). When reinstalling viewport, take up retaining ring bolts until the gasket just compresses the viewport. Do not overcompress the gasket.

    b. Weldment Leaks - Contact appropriate technical authority for guidance on corrective action.

3. Repeat Steps 1 and 2 until all the leaks have been eliminated.
4. Pressurize lock to maximum chamber operating pressure (not hydrostatic pressure) and hold for 5 minutes.
5. Depressurize the lock to 165 feet (73.4 psig). Hold for 1 hour. If pressure drops below 145 feet (65 psig), locate and mark leaks. Depressurize chamber and repair leaks in accordance with Step 2 above and repeat this procedure until final pressure is at least 145 feet (65 psig).
6. Repeat Steps 1 through 5, leaving inner door open and the outer door closed. Leak test only those portions of the chamber not previously tested.

---

* All NOAA standard recompression chambers are restricted to a maximum pressure of 100 psig, regardless of design pressure rating.

too large and heavy for efficient use in the crowded conditions of a chamber.

Although static sparks should be avoided, the atmosphere in a chamber is usually humid enough to suppress sparks. Also, static sparks are only a hazard with vapors, gases, or dry, finely divided materials, none of which should be present in a chamber. Static sparks usually can be prevented by using conductive materials and by grounding everything possible. In some medical hyperbaric chambers, the patient himself is grounded with a wrist strap.

Although the heat of compression is more of a problem in the piping of oxygen-rich gases, it is also a factor in chamber safety. Because gases heat up when compressed, the sudden opening of a valve, which allows an oxygen mixture to compress in the pipes, can cause an explosion. A different but related hazard is the gas flow through a filter or muffler in the air supply. If the air is produced by an oil-lubricated compressor, some oil may collect on the filter or muffler and be ignited by compression or sparks generated by flowing gas.

Incredible as it may seem, a major source of chamber fires has been smoking. This is less of a hazard now than before the risks were widely known, but the pro-

Table 6-5
Standard NOAA Recompression Chamber Air Pressure and Leak Test

Ship/Platform/Facility ____________________

Type of Chamber: Double Lock Aluminum
Double Lock Steel
Portable Recompression Chamber
Other* ____________________
* (Description)

NAME PLATE DATA

Manufacturer ____________________

Date of Manufacture ____________________

Serial Number ____________________

Maximum Working Pressure ____________________

Date of Last Pressure Test ____________________

Test Conducted by ____________________
(Name/Rank/Title)

1. Conduct visual inspection of chamber to determine if chamber is ready for test.

Chamber satisfactory ____________ Initials of Test Conductor ____________

Discrepancies of inoperative chamber equipment:

____

____

____

____

2. Close inner lock door and with outer lock door open, pressurize inner lock to 100 fsw (45 psig) and verify that the following components do not leak:

(Note: If chamber has medical lock, open inner door and close and secure outer door.)

Inner lock leak checks

A. Shell Penetrations and Fittings ____________________
Satisfactory

B. Viewports ____________________
Satisfactory

C. Door Seals ____________________
Satisfactory

D. Door Dog Shaft Seals ____________________
Satisfactory

E. Valve Connections and Stems ____________________
Satisfactory

F. Pipe Joints ____________________
Satisfactory

G. Shell Welds ____________________
Satisfactory

3. Increase inner lock pressure to 225 fsw (100 psig) operating pressure (not hydrostatic pressure) and hold for 5 minutes.

Record Test Pressure ____________ Satisfactory ____________ Initials of Test Conductor
(NOTE: Disregard small leaks at this pressure)

Table 6-5
(Continued)

4. Depressurize lock slowly to 165 fsw (73.4 psig)

Secure all supply and exhaust valves and hold for 1 hour.

Start time ______________________ Pressure 165 fsw

End time ______________________ Pressure ___ fsw

Criterion: If pressure drops below 145 fsw (65 psig), locate and mark leaks. Depressurize, repair, and retest inner lock.

Inner lock pressure drop test passed ______________________

5. Depressurize inner lock and open inner lock door. Secure in open position. Close outer door and secure.

(NOTE: If chamber has medical lock, close and secure inner door and open outer door)

6. Repeat tests of sections 2, 3, and 4 above when setup per section 5. Leak test only those portions of the chamber not tested in sections 2, 3, and 4.

7. Outer Lock Checks

A. Shell Penetrations and Fittings ______________________ Satisfactory

B. Viewports ______________________ Satisfactory

C. Door Seals ______________________ Satisfactory

D. Door Dog Shaft Seals ______________________ Satisfactory

E. Valve Connections and Stems ______________________ Satisfactory

F. Pipe Joints ______________________ Satisfactory

G. Shell Welds ______________________ Satisfactory

8. Maximum Chamber Operating Pressure Test (5 minute hold)

______________________ Satisfactory

__________ Initials of Test Conductor

9. Inner and Outer Lock Chamber Drop Test (Hold for 1 Hour)

Start time ______________________ Pressure 165 fsw

End time ______________________ Pressure ___ fsw

Inner and Outer Lock Pressure Drop Test Passed Satisfactorily

__________ Initials of Test Conductor

10. All above tests have been satisfactorily completed.

____
Test Director Signature — Date

____
Diving Officer/UDS — Date

____
Director, NDP — Date

hibition against smoking in and around chambers must be strictly enforced.

6.5.2 Combustion

The primary factor increasing the risk of fire in a hyperbaric chamber is the increased combustibility caused by the enriched oxygen atmosphere. An enriched oxygen atmosphere is one that either has a partial pressure or an oxygen percentage that is greater than that of air at sea level pressure. The burning rate (determined in a laboratory with paper strips) when the pressure is equivalent to 75 fsw is twice that of sea level air, and it is 2.5 times as fast at 165 fsw.

An additional hazard is introduced when the gas mixture in the chamber also has an increased percentage (i.e., fraction) of oxygen. The relationships among flammability, partial pressure, and oxygen fraction are complex and non-linear, but show a consistent trend toward faster burning with increased oxygen percentage or with an increasing pressure at the same oxygen percentage (Figure 6-5). The nature of the background gas is important, too, with helium requiring higher ignition temperatures but allowing faster burning.

Because of the greatly increased risk when oxygen is added to the chamber atmosphere, it is now considered essential to use an overboard dump system for exhaled gas when divers are breathing oxygen by mask during a decompression or treatment. It is also considered acceptable if a low oxygen level can be maintained by ventilating or purging the chamber with air, but this is a less desirable option because the gas used for purging is itself fairly rich in oxygen. It takes high flows to keep the oxygen within accepted limits, and high flows may be accompanied by excessive noise and compressor wear and tear. The "zone of no combustion" concept is helpful in the management of fire safety in chambers. This concept takes into account the fact that, although changes in pressure at a constant oxygen percentage affect burning rate, changes in the percentage of oxygen have a greater effect. As a result, there is a "zone" of pressure and oxygen percentage that provides adequate oxygen for respiration but that will not support combustion (Shilling, Werts, and Schandelmeier 1976; Rodwell and Moulton 1985). This is illustrated in Figure 6-6. An important consequence of the zone of no combustion is that the chamber environment in most saturation dives is fire safe except in the later stages of decompression. The existence of this zone allows for controlled combustion, such as that of welding, to be performed safely at pressure. In addition to the zone of no combustion, there is a broad pressure-oxygen percentage zone of incomplete or reduced combustion.

6.5.3 Materials

The third element required to make a fire is fuel, i.e., something to burn. Chamber fire safety requires that all combustible materials in the chamber be kept to a minimum, and that, where possible, materials that are not flammable in enriched oxygen be used. Some materials regarded as non-flammable in air will burn in a high oxygen mixture, so it is best to rely on materials known to be safe or relatively safe in oxygen.

Metals are safe, as are ceramics. For wiring insulation, TFE (Teflon®) is probably the best all-around material, but there are mineral insulations and fiberglass, as well as some hard plastics like Bakelite® and Melmac® that are usable in some circumstances. Some fluorine-based elastomers are relatively safe in high oxygen mixtures, but their conductive properties are poor and they are expensive. For clothing, the popular choice is Durette®, but Nomex® is also adequate. Beta fiberglass is suitably flameproof but has undesirable wearing properties (Dorr 1971).

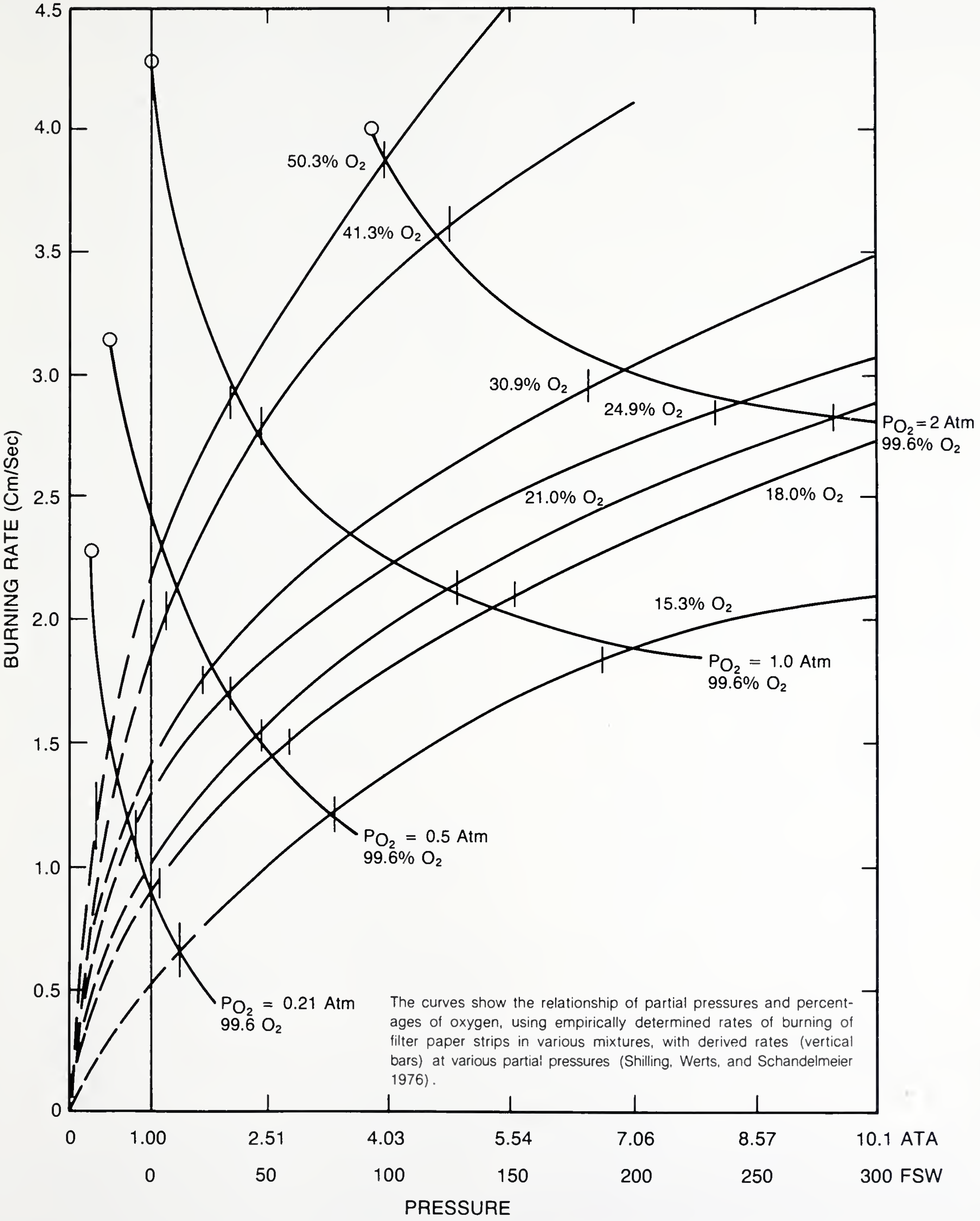
Although chamber design is important to fire safety, even the well-designed chamber needs to be used properly to be safe. Good housekeeping is mandatory; all loose clothing, papers, and other flammable materials must be stowed or removed from the chamber when it is being operated beyond the fire-safe zone. Particularly important to eliminate are fuzzy or powdered or finely divided materials and flammable liquids and gases.

One flammable gas that may come into increasing use in diving is hydrogen. The use of this gas is being explored for deep diving because of its physiological properties (primarily its low density, which results in low breathing resistance). Hydrogen can be used without danger of explosion (once it is properly mixed) when a mixture contains less than 5 percent oxygen, making it suitable for diving deeper than 100 fsw. Most of the safety problems associated with the use of hydrogen as a diving gas occur during handling and mixing.

6.5.4 Management of a Fire

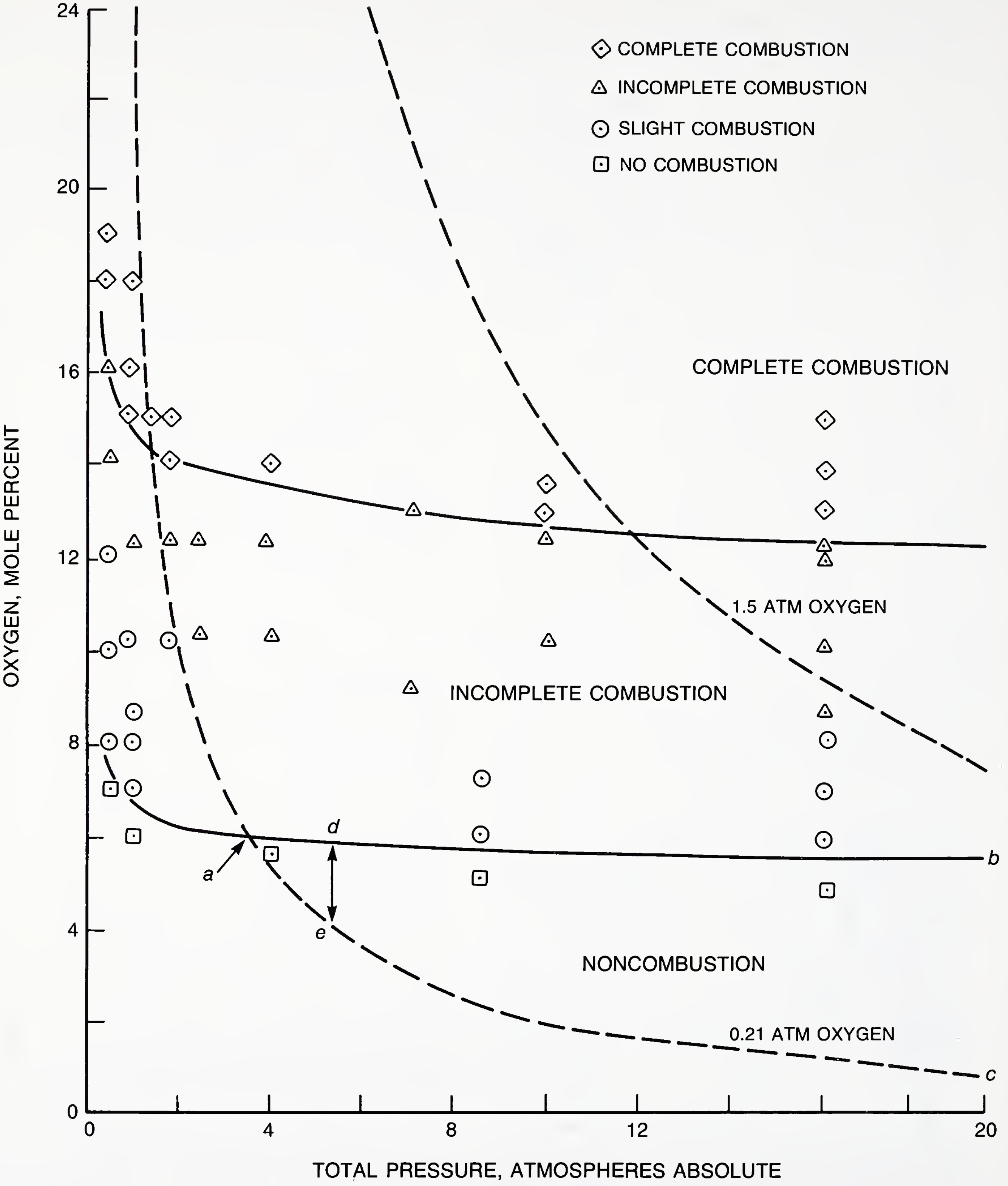
The preceding sections addressed the prevention of chamber fires. Another component of fire safety requires that the people involved be able to deal with a fire once it starts. Although some past chamber fires have spread rapidly (National Fire Protection Association 1979), many others have been extinguished without loss of

Figure 6-5
Burning Rates of Filter Paper Strips at an Angle of 45° in N_2-O_2 Mixtures



The curves show the relationship of partial pressures and percentages of oxygen, using empirically determined rates of burning of filter paper strips in various mixtures, with derived rates (vertical bars) at various partial pressures (Shilling, Werts, and Schandelmeier 1976).

Figure 6-6
Combustion in N_2-O_2 Mixtures Showing the Zone of No Combustion



Combustion zones are defined by solid lines and normal respiration by dashed lines. The area A-D-E is compatible with respiration for prolonged periods, while the area represented by A-B-C is safe to breathe for short periods only (adapted from Shilling, Werts, and Schandelmeier 1976).

life. It is therefore essential that chamber personnel be trained in fire safety techniques.

6.5.4.1 Detection

Numerous fire detection mechanisms are available for routine fire protection. Many of these systems are usable in a pressure chamber, particularly ones operating at the relatively low pressures used with compressed air. The detection mechanisms most suitable for chamber use are those involving infrared or ultraviolet sensors. Ionization or smoke detectors may also be of value.

There are two problems with fire detection systems: false alarms and failure to detect a fire quickly enough. Any detection system needs to be studied thoroughly in the context of the uses and needs of the particular installation. Most experts feel, for example, that a clinical hyperbaric chamber treating patients with open wounds should have an alarm system only, rather than one that automatically deluges the chamber; a preferred approach is to have both a hand-held directable fire hose inside and switches to activate a general deluge system easily available to both chamber occupants and the topside crew. Whether a deluge or alarm system is used, it should be thoroughly tested at the time of installation and periodically thereafter.

The best protection against fire is an alert chamber crew that is backed up by detectors. During certain welding operations in compressed air, the only dependable detection system is another person standing by to watch the operation. It is best if the designated "fire watch" person stands inside the chamber rather than outside (Hamilton, Schmidt, and Reimers 1983).

6.5.4.2 Extinguishment

Fire extinguishment is accomplished by physical, or a combination of physical and chemical, actions involving four basic mechanisms:

- The combustible material can be cooled to a temperature below that required for ignition or the evolution of flammable vapors.
- The fire can be smothered by reducing the oxygen or fuel concentration to a level that will not support combustion.
- The fuel can be separated from the oxidizer by removing either the fuel or the oxidizer or by mechanically separating the two. Mechanical protein foams operate in this fashion by blanketing the fuel and separating it from the oxidizers.
- The reactions occurring in the flame front or just before the flame front can be inhibited or interfered with through the use of chemicals.

At present, the best fire extinguishing agent for use in hyperbaric chambers is water. Water extinguishes primarily by cooling and works best if it strikes the flame or wets the fire in spray form. The pressure at the spray nozzle must be 50 psi or more above chamber pressure to produce the desired degree of atomization and droplet velocities. Simultaneous with the discharge of water, all electrical power to the chamber should be shut off to prevent shorting and electrical shocks to personnel in the chamber; lights must of course remain on. A manually directable fire hose will permit occupants of a chamber to control small localized fires. The fire suppression system should be tested periodically under chamber operating conditions.

6.5.4.3 Breathing Masks and Escape

Most fire fatalities are caused by smoke inhalation rather than burns. Accordingly, the first thing the occupants of a chamber with a fire should do unless immediate escape is possible is to don a breathing mask. The masks should be handy and should have a breathable gas on line or be controllable by the occupants at all times. If it is possible for occupants to flee quickly to another chamber or compartment that can be sealed off from the fire, they should do so rather than donning masks and trying to extinguish the fire.

6.5.5 Summary of Fire Protection Procedures

A summary of chamber fire prevention procedures follows:

- Maintain oxygen concentration and partial pressure as low as possible, preferably within the region of non-combustion. Use an overboard dump system whenever pure oxygen is breathed by mask in a chamber.
- Eliminate ignition sources.
- Minimize combustibles, with the complete exclusion of flammable liquids and gases.
- If combustible materials must be employed, the type and quantity and their arrangement in the chamber must be carefully controlled.
- Firewalls and other containment techniques should be utilized to isolate high-risk fire zones.
- The extinguishing system should involve a water deluge spray that can be activated either by occupants or topside operators and a hand fire hose that can be controlled and directed by the chamber occupants.
- A mask with an appropriate gas on line should be available for each chamber occupant at all times.
- Escape to another chamber or directly into the sea should be the first option in the fire safety operations plan, whenever feasible.

SECTION 7
DIVER AND SUPPORT PERSONNEL TRAINING

DIVER AND SUPPORT PERSONNEL TRAINING 7

7.0 GENERAL

This section describes the general content of diver training programs, the training involved in preparing to dive under specialized circumstances, and basic approaches to diver training. It does not prescribe specific training procedures or attempt to teach divers how to perform specific underwater tasks.

Many organizations offer diver training. NOAA and the Navy are among those government agencies that train divers in support of agency missions. Many colleges and universities offer diver training to students and faculty members who use diving as a research tool. Diver training also is available from diver certification organizations and local dive shops. Commercial diving schools offer extensive diver training for divers in the commercial diving industry. These training organizations select students on the basis of their personal motivation, physical fitness, and basic swimming skills. This section emphasizes the training of NOAA divers and other personnel, but many of the principles described here apply to the training of all divers.

7.1 NOAA DIVERS

NOAA-certified divers include NOAA Corps officers, researchers, diving technicians, and individuals from universities and organizations involved in NOAA-sponsored programs that require diving skills. NOAA also trains divers from other Federal agencies. All of the candidates who apply to NOAA's diving program are volunteers.

The amount and type of diving involved in the different NOAA programs can vary greatly: NOAA divers include senior researchers who dive only occasionally in shallow water as well as divers who are required to dive regularly as part of their normal duties. The selection and training of NOAA divers are monitored carefully by the NOAA Diving Program.

7.1.1 Selection Standards

NOAA divers are selected from volunteers on the basis of their psychological and physical fitness and their water skills. The psychological evaluation for acceptance into the program consists of a personal interview, an assessment of motivation, and a general screening by experienced NOAA divers to identify individuals who are unlikely to be able to handle the stresses of operational and research diving. The evaluation interview helps to identify any misconceptions the candidate may have about training or the requirements, conditions, and responsibilities of subsequent NOAA diving work.

7.1.2 Physical Examination

The physical examination of divers to determine if they are *medically* qualified to dive requires evaluation by a trained hyperbaric physician. Military, commercial, and scientific divers are evaluated according to standards set forth by their respective agencies or organizations. NOAA has developed and enforces medical standards for its divers.

Many medical conditions disqualify a person for diving with compressed gas, and other medical conditions increase the risk of serious injury or disability in the diving environment. The guidelines below present a framework for individual dive fitness evaluations; they are not established standards. These guidelines are organized in accordance with a systems approach, and no attempt is made to rank systems in terms of their relative importance.

Skin

- Any chronic or acute dermatitis adversely affected by prolonged immersion should be disqualifying.
- Allergy to materials used in diving equipment that comes into contact with the skin is a relative contraindication.
- History of sensitization or severe allergy to marine or waterborne allergens should be disqualifying.

Psychiatric

- Acute psychosis should be disqualifying.
- Chronic or acute depression with suicidal tendencies should be disqualifying.
- Chronic psychosis in partial remission on medication should be disqualifying.
- Substance use or abuse, including abuse of alcohol or use of mood-altering drugs, should be disqualifying.
- Careful attention should be paid to the maturity of prospective candidates, their ability to adapt to

stressful situations, their motivation to pursue diving, and their ability to understand and follow decompression tables and directions.

Neurologic

- Closed head injury; following full recovery, any neurologic deficit (including an abnormal EEG or post-traumatic seizures) should be disqualifying.
- Spine injury, with or without cord damage, may carry an increased risk of decompression sickness and attendant lower extremity paralysis. Prior cord decompression sickness with residual symptoms should be disqualifying. Herniated nucleus pulposis of the lower back (if corrected) should be evaluated on an individual basis, as should peripheral neuropathy.
- Any disorder that causes or results in loss of consciousness should be absolutely disqualifying. This includes any form of seizure, previous gas embolism, or prior cerebrovascular accident (due to regional perfusion abnormalities that would predispose to decompression sickness).
- Diving after intracranial surgery should be evaluated individually; however, it is not an absolute contraindication. Issues to be considered include absence of seizures, presence of residual neurologic deficit, and impairment of regional perfusion.

Ophthalmologic

- Candidates should demonstrate adequate visual acuity to orient themselves in the water and on a boat. Corrective lenses, either fixed to the face mask or soft contact lenses (which allow for gas transfer), are acceptable.
- Narrow-angle glaucoma, aphakia with correction, motility disorder, cataract, and retinitis pigmentosa are relative disqualifications for diving; a skilled ophthalmologist should be consulted.
- Because color vision is required for certain diving tasks, deficiencies in color vision may be disqualifying.

Otolaryngologic

- As a prerequisite to diving, candidates must have intact tympanic membranes and be able to auto-inflate the middle ear. Performing a Valsalva or Toynbee maneuver can be used to indicate whether the candidate can inflate his or her middle ear (inability to do so predisposes to rupture of the tympanic membrane or round window).
- Tympanic membrane perforations should be disqualifying (an opening in the tympanic membrane would allow water to get into the middle ear). If a tympanic membrane rupture is completely healed or has been surgically repaired and the candidate is able to auto-inflate, he or she may be conditionally cleared for diving with the warning that the perforation may recur.
- Active ear infection should be temporarily disqualifying.
- Chronic or acute otitis externa should be disqualifying until healed.
- Meniere's disease and other conditions that are associated with vertigo should be disqualifying.
- Extensive mastoid surgery, stapedectomy, or artificial cochlear implant should be disqualifying.
- Barotitis should be disqualifying until all middle ear inflammation and fluid have resolved and tympanic membrane motility has returned to normal.

Nose and Paranasal Sinuses

- A patent nasal passage and the absence of sinus and nasal congestion are essential in diving.
- Nasal polyps, deviated nasal septum, and other obstructive nasal lesions should be corrected before diving is permitted.
- Acute or chronic infection should be disqualifying.
- A history of long-term decongestant use should trigger a search for the cause of the congestion, and candidates should be warned about the dangers of the chronic use of chemical agents while diving.

Oral and Dental

- Candidates must be able to be fitted with and hold a scuba mouthpiece.
- Where there is a danger that trapped gas could get under a tooth and rupture it, diving should not be permitted.
- Badly decayed or broken teeth should be disqualifying.

Pulmonary

- Because any abnormality in pulmonary system function can cause arterial gas embolism, pneumothorax, or pneumomediastinum, the following conditions should be absolute disqualifications for diving:

  —Bronchial asthma;
  —History of traumatic or spontaneous pneumothorax;
  —Previous penetrating chest trauma or surgery of the chest;
  —Chronic obstructive lung disease;
  —Active pneumonia or lung infection, including active tuberculosis; and
  —Mycotic (fungal) disease with cavity formation.

- Long-term cigarette smoking increases the risk of pulmonary complications while diving.

- All candidates should be given a screening chest x ray to determine if they have a disqualifying lesion.

Cardiovascular

- Cardiovascular defects can be disqualifying because they predispose the individual to unacceptable risks. Conditions that should be disqualifying are:

  —Cyanotic heart disease;
  —Aortic stenosis or coarctation of the aorta;
  —Prosthetic heart valves;
  —Exercise-induced rhythm disorders, including disorders that manifest as paroxysmal tachycardias despite control with drugs;
  —Heart block;
  —Cardiac or pulmonary A-V shunts;
  —Candidates with pacemakers should be individually evaluated and generally should be disqualified.

- Coronary artery disease should be evaluated by an expert.
- Peripheral vascular disease requires case-by-case evaluation.
- Candidates taking cardiovascular drugs (including blood pressure medication) should be evaluated on a case-by-case basis. The use of beta blockers increases the risk of bronchospasm and suppresses the stress response.
- Hypertension should be considered on a case-by-case basis.

Hematological

- Sickle cell anemia should be disqualifying.
- Leukemia or pre-leukemia manifesting as myelofibrosis and polycythemia should be disqualifying.
- Anemia is relatively disqualifying and requires case-by-case evaluation.
- Intoxication that has caused methemoglobinemia should be disqualifying.

Gastrointestinal

- Any disorder that predisposes a diver to vomiting should be disqualifying (including Meckel's diverticulum, acute gastroenteritis, and severe sea sickness).
- Unrepaired abdominal or inguinal hernia should be disqualifying.
- Active peptic ulcer disease, pancreatitis, hepatitis, colitis, cholecystitis, or diverticulitis should be disqualifying until resolution.

Endocrinological

- Diabetes mellitus should be disqualifying unless it is diet controlled.
- Obesity increases the relative risk of developing decompression sickness because of the decrease in gas diffusion through adipose tissue.
- Other endocrine abnormalities should be evaluated on a case-by-case basis.

Musculoskeletal

- Paralytic disorders should be relatively disqualifying.
- Bone fractures that are incompletely healed and osteomyelitis that is actively draining should be disqualifying.
- Deformities, either congenital or acquired, that impair the candidate's ability to use scuba equipment should be disqualifying.
- Inadequate physical fitness to handle the physical work of diving should be disqualifying.

Obstetric and Gynecological

- Pregnancy should be absolutely disqualifying because of the risk of bubble formation in the developing fetus during decompression.

7.1.3 Swimming Skills

All applicants for diver training should perform the following swimming exercises without face masks, fins, or snorkels and with confidence and good watermanship:

- Swim 300 yards (274 meters) using the crawl, sidestroke, and backstroke
- Swim under water for a distance of 50 feet (15.2 meters) without surfacing
- Stay afloat for 30 minutes.

7.1.4 Scuba Training

Although NOAA has its own diver training and certification program, NOAA personnel often receive basic scuba training before they become NOAA diver candidates. Regardless of the training organization, however, there are basic practices and procedures that should be included in any scuba training program. For example, any diver training program should produce:

- Divers who reach a level of competence that will permit safe open-water diving
- Divers who can respond to emergency situations and make appropriate decisions when faced with problems under water
- Divers who can execute assigned underwater tasks safely and efficiently.

Diving procedures, particularly those of a lifesaving nature, should be overlearned to ensure automatic response in emergencies, which reduces the likelihood of the diver losing control and panicking (Bachrach and Egstrom 1986).

Although training courses vary widely among organizations with respect to length, content, complexity, and water skills required, all courses should include both classroom sessions and in-water training. The core of a training program for working divers should follow the guidelines discussed in Sections 7.1.4.1 and 7.1.4.2.

7.1.4.1 Classroom

Classroom lectures using multimedia presentations should be developed to provide the candidate with as much knowledge as possible. It is important for the candidate to develop a general understanding of diving principles and the diving environment, and the self-confidence (but not overconfidence) necessary to operate safely in the field.

Formal training courses are only the first step in becoming a safe and efficient diver. With this in mind, diver training should expose the trainee to a wide variety of diving-related experiences in addition to teaching the basics. Details of various diving systems and ancillary equipment will be learned as part of on-the-job training. Topics to which working and research divers should be exposed during basic and advanced training include:

- Diving physics: pressure, temperature, density, specific gravity, buoyancy, diving gases, the kinetic theory of gases, and the gas laws and their practical application in diving;
- Diving physiology and medicine: the anatomy and mechanics of circulation and respiration, the effects of immersion on the body, hypoxia, anoxia, hypercapnia, hypocapnia, hyperpnea, apnea, hyperthermia, hypothermia, the direct effects of pressure (squeeze, lung overpressure, and "diver's colic"), the indirect effects of pressure (decompression sickness, gas embolism, inert gas narcosis, oxygen toxicity, bone necrosis), breathing gas contaminants, drowning, near-drowning, overexertion, exhaustion, breathing resistance, "dead space," and psychological factors such as panic;
- Equipment: selection, proper use, and care of personal gear; air compressors and compressor systems; operation and maintenance; tank-filling procedures; requirements for testing and inspection of specific types of equipment (including scuba cylinders); and air purity standards and testing;
- Diving platforms: shore, small boat, and large vessel platforms; fixed structures; safety precautions and surface-support requirements in vessel diving; and water entry and exit;
- Operations planning: objectives, data collection, definition of tasks, selection of equipment, selection of dive team, emergency planning, special equipment requirements, and setup and check out of support platforms;
- Principles of air diving: introduction to decompression theory, definition of terms, structure and content of diving tables, single and repetitive diving principles, practical decompression table problems (including decompression at altitude), and calculation of air supply requirements;
- Diving procedures: relationship of operations planning to diving procedures; warning signal requirements; hand and line signals; recall; water emergencies; buddy teams; tending; precautions required by special conditions, e.g., pollution, restricted visibility, currents; "dive safe ship" requirements; boating safety; dangers of diving at high altitude or flying after diving; dive station setup and post-dive procedures; work procedures for search and recovery; salvage and object lifting; instrument deployment and maintenance; and underwater navigation methods;
- Accident prevention, management, and first aid: basic principles of first aid, cardiopulmonary resuscitation (CPR), use of oxygen resuscitators, development of accident management plans, recovery of victims and boat evacuation procedures, recognition of pressure-related accident signs and symptoms, patient handling en route to treatment, introduction to recompression chambers and treatment procedures, and procedures for reporting accident investigations (see Sections 18 and 19); and
- Diving environment and hazardous marine life: tides and currents (surf; thermoclines; arctic, temperate, and tropical conditions); waves and beaches; rip currents; and river, harbor, and marine life hazards.

7.1.4.2 Pool and Open-Water

A program of work in the water that progresses from pool to protected open water and then to a variety of open-water situations is essential to diver training. Students should be exposed to open-water conditions while diving at night, under conditions of reduced visibility, and in cold water (see Section 10 for details of diving under special conditions). An understanding of the proper use of mask, fins, and snorkel; surface swimming; surface dives; underwater swimming; pressure equalization; and rescue techniques is required to master skin (breath-hold) and scuba diving.

Breath-hold or skin diving is hazardous, and working and research divers using this technique must be competent swimmers in excellent physical condition. The skin diver is subject to barotrauma of the ears and sinuses, just as any other diver is; however, air embolism and related complications are a problem only if the skin diver breathes air from a scuba cylinder, a habitat, or an underwater air pocket. Since breath-holding can cause serious problems, divers should thoroughly understand the potential hazards of prolonged breath-holding under pressure.

Specific skills to be learned in a pool and open-water program should include but not be limited to:

- Skin diving skills

  —equalization of air spaces
  —mask clearing and equalization
  —snorkel clearing
  —proper use of buoyancy compensator
  —proper use of weight belt (including how to ditch it)
  —proper kicks with and without fins
  —distance swimming with full skin-diving gear
  —water entries and surface dives

- Skin diving confidence drills

  —recovery of mask, snorkel, and fins
  —clearing the ears
  —one-finned kicks over a distance
  —snorkeling without mask

- Lifesaving skills

  —search and recovery
  —proper rescue entries
  —rescue techniques with and without a buoyancy compensator
  —rescue carries
  —in-water mouth-to-mouth artificial resuscitation

- Skills involving the use of scuba equipment

  —air sharing
  —"ditch and don" exercises
  —mask clearing
  —regulator recovery and clearing
  —emergency ascent
  —station breathing
  —scuba entries
  —buoyancy control
  —gauges and other special life support equipment
  —scuba rescues.

Experience and experimental data have shown that the diver should be trained to maintain a reasonably constant respiration rate with a nearly complete inhalation and exhalation pattern. This slow deep-breathing pattern permits good air exchange at relatively low flow rates. Keeping the flow rate at lower levels results in more comfortable breathing; higher respiration rates can cause discomfort and anxiety (Bachrach and Egstrom 1986).

7.1.5 Umbilical Dive Training

Umbilical diving is also referred to as surface-supplied diving. In umbilical diving, the diver's breathing gas is supplied via an umbilical from the surface, which provides the diver with an unlimited breathing gas supply.

Preliminary selection procedures and criteria for umbilical dive training are essentially the same as those for basic scuba. In NOAA, divers applying for umbilical training must be certified as advanced working divers, which requires the completion of at least 100 logged dives. Before qualifying as umbilical divers, trainees should receive instruction and training in:

- The general purpose and limitations of surface-supplied (umbilical) diving;
- Use of masks and helmets;
- Assembling and disassembling of the gas supply system;
- Use of accessory tools and equipment basic to umbilical procedures and specific to the particular tasks being contemplated;
- Methods of achieving intelligible communication;
- Equipment repair and maintenance;
- Water entry, descent, and ascent procedures and problems.

When initial training is completed, an open-water qualification test that includes both general diving techniques and actual working procedures should be given.

Qualification Test

To pass the qualification test, candidates must demonstrate the ability to:

- Plan and organize an air surface-supplied diving operation to depths between 30 and 50 fsw (9.1 and 15.2 msw), including calculation of hose pressure and air requirements and instruction of surface personnel;

- Demonstrate ability to rig all surface and underwater equipment properly, including air supply, mask/helmet, communications, and other support equipment;

- Demonstrate proper procedures of dressing-in and dressing-out, using the particular pieces of equipment needed for the working dive;
- Tend a surface-supplied diver;
- Demonstrate knowledge of emergency procedures (these may differ for each project or exposure) as determined by the instructor or dive master;
- Participate in at least two practice dives, as described below:
  - —Properly enter water that is at least 10 fsw (3 msw) deep and remain submerged for at least 30 minutes, demonstrating control of air flow, buoyancy, mobility, and facility with communication systems.
  - —Ascend and leave water in a prescribed manner.
  - —Properly enter water that is between 30 and 50 fsw (9.1 and 15.2 msw) deep and conduct work-related tasks.

After successful completion of this test, the instructor should evaluate the diver's performance and establish a phased depth-limited diving schedule to ensure a safe, gradual exposure to deeper working depths. Detailed descriptions of umbilical diving equipment and its use appear in Sections 5.2 to 5.2.4.10.

7.1.6 Special Equipment Training

In addition to learning how to operate and maintain diver life-support scuba and umbilical equipment, divers may be called on to use special equipment in the performance of their duties. In such instances, new techniques and procedures must be learned from divers who are already experienced in their use, from technical personnel (such as manufacturers' representatives), or by test and evaluation. Examples of types of equipment that are used by divers and whose use requires special training are: variable-volume suits; thermal protection diving suits; protective suits, clothing, support equipment, and breathing apparatus for diving in contaminated water; photographic/video equipment; scientific equipment; and underwater tools.

Many training programs prepare divers to use special equipment and protective clothing. The topics addressed include:

- Operational Diver Training
  - —Search and recovery techniques
  - —Wireless communications
  - —Lifting of objects
  - —Ships husbandry
  - —Underwater television systems
  - —Pinger/sonar locators
  - —Underwater tools
- Variable-Volume Dry Suit Training
  - —Suit selection, preparation, and maintenance
  - —Emergency procedures for blowups, weighting, buoyancy control
  - —Control of operational problems
  - —Hypothermia/hyperthermia
  - —Accessories
  - —In-water training
  - —Cleanup and decontamination after polluted-water dives
- Contaminated-Water Diving Training
  - —Protective systems
  - —Donning and doffing
  - —Buoyancy control
  - —Hyperthermia
  - —Training as a tender
  - —Work performance while fully suited
  - —Decontamination procedures.

7.1.7 Mixed-Gas Training

Mixed-gas diving involves the use of a breathing medium other than air; this mixture may consist of nitrogen-oxygen, helium-oxygen, or oxygen and one or more inert gases.

The curriculum for NOAA's mixed-gas training program includes coverage of the following topics:

- Oxygen partial pressure limits
- Nitrogen-oxygen breathing mixtures
- Depth/time limits for oxygen during working dives
- Central nervous system and pulmonary oxygen toxicity
- Nitrogen/oxygen breathing media mixing procedures
- Analysis of mixed-gas breathing media
- Mixed-gas diving equipment (open-circuit systems)
- NOAA Nitrox I no-decompression limits and repetitive group designation table for no-decompression dives
- NOAA Nitrox I equivalent air depths for open-circuit scuba
- NOAA Nitrox I decompression tables
- NOAA Nitrox I residual nitrogen table
- NOAA Nitrox I surface interval table.

NOAA mixed-gas trainees attend classroom sessions and then progress to open-water dives, during which they use a nitrox (68 percent nitrogen, 32 percent oxygen) breathing mixture. Divers enrolled in a commercial diving mixed-gas course or those being trained by their companies receive classroom and open-water training in the use of heliox (helium-oxygen) breathing mixtures. Heliox is a widely used breathing medium in deep mixed-gas diving and in saturation diving.

7.1.8 Saturation Training

Although the basic requirements for saturation diving are the same as those for surface-based diving, there are some important differences that need to be addressed during training. The diver's "home base" during saturation usually is either a seafloor habitat or a diving bell system (see Section 17). For this reason, the saturation diver needs a fundamental reorientation to the environment. For example, the saturation diver must constantly be aware that returning to the surface will complicate, rather than improve, an emergency situation. This factor has specific implications with respect to the selection and use of certain pieces of saturation diving equipment. For example, in saturation diving:

- Weight belts without quick-release mechanisms or weight harnesses should be used;
- Buoyancy compensators with oral inflation tubes rather than a cartridge or tank inflation system should be used;
- Adequate diving suits should be worn because the extended diving time involved in saturation may cause chilling even in tropical regions;
- A self-contained backup breathing gas supply should be used when umbilical equipment is utilized;
- Extra precautions must be taken when filling scuba cylinders to avoid admitting water into the valves.

Because the consequences of becoming lost are so serious, a saturation diving training program also should include training in underwater navigation techniques. Divers should be instructed in the use of navigational aids, such as grid lines, string highways, ripple marks, topographical features, and navigation by compass. Because compasses are not always accurate, divers should be trained to use the compass in combination with topographical and grid line information.

Training in habitat operations, emergency procedures, and local diving restrictions usually is conducted on site. Such training includes instruction in: communication systems; use of special diving equipment; habitat support systems; emergency equipment; regional topography; underwater landmarks; navigational grid systems; depth and distance limitations for diver/scientists; and operational and safety procedures used by the surface support team.

Other features related to seafloor habitation also need to be identified during saturation training. Some of these relate to housekeeping chores inside the habitat. For example, water boils at a higher temperature under water than on the surface: 262°F (128°C) at 50.5 feet (15.4 meters) and 292°F (144°C) at 100 feet (30.5 meters); cooking procedures must be altered, because burned food not only constitutes a fire hazard but produces toxic gases at depth. (For additional information on underwater habitation, see Miller and Koblick (1984).)

A slight loss in speech intelligibility also occurs as a result of the denser atmosphere at depth. The amount of speech distortion depends on the habitat breathing mixture and the depth. Other factors directly affecting the saturated diver or a habitat diving program include: the necessity to pay special attention to personal hygiene, e.g., to take special care of the ears and skin. Because of the high humidity encountered in most habitats, the growth of certain pathogens and organisms is stimulated and recovery is prolonged. Proper washing, drying, and care of diving suits is essential to prevent skin irritation or infections. Trainees should be aware that there are restrictions with respect to the use of toxic materials in a closed-environment system such as a habitat. This applies not only to the use of scientific preparations but also to the use of normally harmless things such as rubber cement (used for the repair of wet suits) and aerosol sprays.

Training for saturation diving from underwater habitats should teach divers the procedures for making ascending and descending excursions from the storage depth. Special diving excursion tables have been developed for excursions from the saturation depth. These tables are designed to consider storage depth, oxygen dose, nitrogen partial pressures, and other factors. Trainees should become familiar with these tables and their limitations.

A unique feature of saturation diving is the diver's ability to make upward excursions. However, upward excursions constitute a decompression, and divers must be careful to remain within the prescribed excursion limits. This applies not only to the divers themselves but also to certain types of equipment; for example, if a camera is opened and reloaded in a habitat, an upward excursion of 10 to 15 feet (3.0 to 4.6 meters) can cause flooding because such equipment is not designed to resist internal pressure. Students should be instructed to check all equipment to be used in a habitat to determine whether it is designed to withstand both internal and external pressures.

7.1.9 Chamber Operator Training

The operation and maintenance of recompression chambers are a necessary part of a diving program; it is therefore important to ensure that all personnel operating recompression chambers are properly trained and certified as chamber operators.

A training program for chamber operators should include the following topics:

- Introduction to hyperbaric chambers;
- Chamber setup and subsystems;
    - —Pre- and post-dive procedures
    - —Plumbing
    - —Controls
    - —Life-support and emergency procedures
    - —Breathing and communication systems
    - —Maintenance procedures
- Recordkeeping;
- Introduction to the physics of pressure;
- Decompression theory and calculation of decompression tables;
- Recompression theory and treatment tables;
- Barotrauma;
- Examination and handling of patients;
- Emergency management of decompression sickness and air embolism;
- Inside tending procedures;
- Chamber medical kit contents and use;
- Review of case histories;
- Hands-on experience with simulated treatments;
- Chamber operation procedures.

7.2 TRAINING OF DIVING SUPERVISORS

Many organizations, including NOAA, the Navy, and commercial diving companies, designate certain experienced divers as supervisors. NOAA has four supervisory diving categories: Line Diving Officer, Unit Diving Supervisor, Diving Instructor, and Divemaster.

Each organization provides training that is specifically related to the goals of the organization; however, all diving supervisors are required to have a broad range of diving experience. In addition, every supervisor must have the working knowledge to plan diving projects, oversee diving activities, conduct inspections, and investigate accidents. Diving supervisors receive advanced training in dive planning, the use of special equipment, first aid, communications, and accident management.

7.3 DIVING MEDICAL TECHNICIANS

Although there are obvious advantages in having a qualified hyperbaric physician at a diving site, this is often not practical. As an alternative, a Diving Medical Technician (DMT) trained in the care of diving casualties can be assigned to the site. An individual so trained can respond to emergency medical situations and can also communicate effectively with a physician located at a distance from the diving site (see Section 19.6.1).

The development of emergency medical service organizations began in the United States in the mid-1970's in response to the need for improved national emergency medical care. The National Highway Traffic Safety Administration of the Department of Transportation developed and implemented a program to train Emergency Medical Technicians (EMT's) at various levels of certification. These services, coordinated by the Department of Transportation, are offered and managed at the state level.

Courses in various aspects of emergency medical care are offered by organizations such as the American Red Cross, the American Heart Association, and local fire and rescue groups. Individuals successfully completing these courses are certified by the sponsoring agency as having fulfilled the course requirements. Courses may lead to different levels of certification, e.g., national, state, local, or regional, and thus may reflect different levels of proficiency.

In the late-1970's, the need for medical technicians specializing in the emergency treatment of diving casualties was recognized; this specialized need arose because existing EMT training programs were heavily oriented toward urban ambulance-hospital emergency systems. The interest in diving medical technicians grew with the development of offshore oil and gas well drilling platforms. Experts decided that the most workable solution to this need was to cross-train working divers as medics rather than to train medics to treat diving casualties. This choice to train working divers as medical technicians was also driven by economic considerations, since using a diver as a medic made it unnecessary to have a person standing by. The National Association of Diver Medical Technicians (NAMDT) was founded in 1981 and, by 1985, a number of training organizations were approved to provide DMT training. NOAA has adopted DMT training for its medical personnel and has a representative on the NAMDT Board of Directors.

The approved DMT training program is an extensive 303-hour course and includes training in the following areas:

Lecture (158 hours)

- orientation, anatomy, medical terminology, legal problems

- basic life support, shock, use of oxygen
- systemic diseases and injuries
- medical, environmental, thermal, diving, and decompression aspects
- equipment use, patient handling, emergency communications
- drugs and fluids

Laboratory and Practical Experience (115 hours)
- patient assessment and care, suturing
- animal laboratory (optional)
- autopsy (optional)
- diving treatment, neurological examination
- chamber operations

Clinical Observation (30 hours)
- mixed ambulance/emergency room experience.

DMT training is based on the EMT Level I Program but includes a number of important additions. Because it may be hours or even days before medical help arrives in an emergency diving situation, the DMT must be capable of delivering more advanced support than a medical technician in an urban area. Accordingly, DMT's receive training in parenteral drug administration, intravenous infusion techniques, pneumothorax stabilization, simple suture techniques, and other special procedures.

DMT's must be recertified every 2 years and must attend 24 hours of lectures and serve 24 hours in an ambulance/emergency room situation to maintain their certification. Serving under the diving supervisor, the trained DMT brings enhanced diagnostic and clinical skills to medically and geographically remote worksites. DMT's also have the ability to implement expert advice received from medical specialists belonging to organizations such as the national Divers Alert Network (see Section 19.6.1), even though these experts are geographically distant from the scene of the diving accident or illness.

7.4 HYPERBARIC PHYSICIANS

A hyperbaric physician is a medical doctor with special training in the treatment of medical problems related to diving and/or elevated atmospheric pressure. Such a physician may be a general practitioner or a specialist in any branch of medicine. In many cases, the personal impetus to become an expert in hyperbaric medicine derives from the fact that the physician is also a diver. Historically, the U.S. Navy and U.S. Air Force have been the primary sources of expertise and trained personnel in hyperbaric medicine.

Because of the increase in the number of divers, however, the need for physicians trained to treat diving casualties has increased. In response to this need, several organizations offer specialized training. These courses range from a series of lectures to more intensive courses lasting several weeks. The best source of information on the availability of courses in hyperbaric medicine is the Undersea and Hyperbaric Medical Society, Inc., which is located in Bethesda, Maryland.

One of the most respected and comprehensive training courses in hyperbaric medicine is the 3-week program offered by NOAA. Started in 1977 with financial support from the Department of Energy and the cooperation of the U.S. Navy, this program has trained over 269 physicians to date. The course includes training in the following areas:

- diving physics
- basic diving physiology
- fundamentals of inert gas exchange
- stress physiology and behavior
- oxygen toxicity
- air embolism
- vestibular problems related to diving
- saturation diving
- commercial diving equipment
- decompression tables
- decompression sickness and treatment
- helium-oxygen tables and recompression treatment
- recompression chamber operation and safety procedures
- gas analysis systems
- pressure exposures in recompression chambers
- hyperbaric oxygen therapy
- emergency treatment of diving casualties
- orientation to the national Divers Alert Network (DAN)
- basics of diving accident management
- case histories of diving accidents and treatment
- polluted-water diving
- treatment of near-drowning victims
- evaluation and assessment of scuba diver injuries and illnesses.

Physicians trained in hyperbaric medicine are an important resource for the diver. Every diver should learn the name, address, and phone number of the nearest hyperbaric facility and/or hyperbaric physician in his or her area. In the event of a diving accident related to pressure, such as an embolism or decompression sickness, it is essential to have located a physician trained in hyperbaric medicine before beginning the dive. Hyperbaric chambers are described in Section 6, and the treatment of diving casualties is discussed in Section 20.

7.5 RESEARCH DIVERS

Research diver training is offered by NOAA and a number of educational institutions and marine laboratories. Although the course content and style differ with different organizations, the objective of such courses is either to train experienced divers in scientific techniques and methods to enable them to act as underwater scientific technicians or to train experienced scientists in the techniques and methods of underwater work. In either case, the curriculum should include advanced instruction in diving physiology, uses of underwater equipment, and a review of the potential hazards faced by divers.

Each of these factors should be related to the problems faced by diving scientists and their impact on the conduct of underwater investigations. Diving safety should be emphasized throughout the course so that on completion of training the divers feel completely comfortable in the water and are able to concentrate their energies on the work or scientific tasks at hand. This degree of competence can be achieved only if the basic diving skills are learned so thoroughly that routine operations and responses to emergencies become automatic.

University research diver training programs have historically lasted for a minimum of 100 hours and required candidates to complete 12 open-water dives. In 1984, the Occupational Safety and Health Administration (OSHA), which had promulgated regulations in 1978 governing commercial diving operations, specifically exempted from these regulations those scientific and educational diving programs that could meet certain requirements. A research organization or educational entity wishing exemption from the Federal OSHA standard must have in place a diving program that has developed a diving manual, has a diving control officer and diving safety board, and has developed procedures for emergency diving situations. The program used by many research organizations to fulfill these requirements for exemption was originally developed at the Scripps Institution of Oceanography in the 1950's and has been updated since then as new technologies and techniques have become available.

The safety record of the research diving community reflects the effectiveness of current diver training and certification procedures. Individuals or organizations wishing information about scientific diving programs should contact the American Academy of Underwater Sciences (947 Newhall Street, Costa Mesa, California 92627). As a result of the combined experience of scientific diving organizations, a set of standards has been developed to ensure that the high level of quality and the success of scientific diving are maintained (American Academy of Underwater Sciences 1987).

7.5.1 Selection

Selecting individuals for research diver training depends on the objectives of the particular course. The acceptance of individuals for such training should be based on need, academic background, personal motivation, and the ability to pass certain swimming and fitness requirements. If possible, individuals with common objectives should be grouped together and trained in a single class.

Selection criteria should require research diver-candidates to demonstrate evidence of:

- Diver certification from a recognized organization
- Satisfactory completion of a physical examination
- Good physical condition
- Need for the specialized training
- Training in the basics of first aid, including CPR
- Training or equivalent experience in research methods
- Ability to pass diving and swimming skill tests to the satisfaction of the examiner.

Research divers must be comfortable in the water and know their limitations and those of their equipment. To accomplish these ends, a series of pretraining tests are used to predict likely success in the diving environment. The following phases are included in the pretests:

Phase 1—Swimming Pool

This series of activities is to be completed within a 15-minute period and should be done without mask, fins, or snorkel and in the following sequence:

1. Perform a 75 foot (22.9 meter) underwater swim on a single breath.
2. Perform a 1000 foot (304.8 meter) swim on the surface in less than 10 minutes, using the breast or side stroke.
3. Perform a 150 foot (45.7 meter) underwater swim, surfacing for no more than 4 single breaths during the swim.

The 75 foot (22.9 meter) underwater swim simulates a 75 foot (22.9 meter) emergency ascent, except that the exhaling is omitted. The 1000 foot (304.8 meter) surface swim simulates a swim back to the beach. The 150 foot (45.7 meter) underwater swim, surfacing for 4 single breaths, simulates surf passage, where one has to surface, take a breath, and get back under water before the next wave.

The candidates are then required to swim 75 feet (22.9 meters), dive to the bottom of the pool, recover, and tow a person of similar size 75 feet (22.9 meters).

Phase 2—Open-Water Test

An ocean or other open-water swim involves a 1000 foot (304.8 meter) open-water swim and a dive to the bottom in a depth of at least 15 feet (4.6 meters). This open-water exercise often reveals potential problems that are not apparent when the candidate swims in a swimming pool. The diver training success rate among those screened by means of these two tests at the Scripps Institution of Oceanography has been nearly 100 percent (Stewart 1987).

7.5.2 Curriculum

Research diver training should cover dives conducted in as many different environments as possible. Additionally, students should gain experience using a variety of different platforms, such as small boats, ships, piers, docks, and jetties, and should make water entries under as many shore conditions as practical.

The curriculum should be tailored to the local area and the particular needs of the researcher. However, the following outline identifies topics that are usually addressed in a practical scientific diving course:

- A review of diving physiology and physics as they relate to field operations;
- Surface-supplied diving techniques, including tending, communications, capabilities of surface-supplied diving systems, and emergency procedures;
- Small boat handling, including the uses and limitations of small craft as diving platforms, load limits and distribution, securing procedures, minor field repairs, and legal responsibilities;
- Equipment handling, including safe use, field maintenance, and storage of diving and scientific equipment;
- Underwater rigging, including emplacement, moving, and securing of research equipment in the water;
- Environmental hazards, such as: diving in currents, polluted water, blue water, restricted areas such as caves, under ice, and in wrecks, and under conditions of limited visibility;
- Thermal protection problems, including the use of wet suits, variable-volume dry suits, and hot water suits, and the advantages and disadvantages of each;
- Diver communication, including diver tending, hardwire, and acoustic and diver recall systems;
- Operational planning, including diver supervision, scheduling, and emergency plans;
- First aid, including CPR;
- Diving accident management procedures;
- Underwater navigation and search methods, including methods of locating, marking, and returning to research sites;
- Collection techniques, including introduction to sampling, testing, and harvesting systems, tagging, preserving, transporting of specimens, and data recording methods;
- Photographic documentation, including the use of still, video, movie, and time-lapse photography for scientific investigations.

7.6 EQUIPMENT MAINTENANCE

Training in equipment maintenance is an important element in any diving program. Although fatal diving accident statistics show that equipment failure is rarely the cause of death (see Section 19.2), equipment malfunction does cause near-misses, lost time, inconvenience, and premature dive termination. Only trained and qualified personnel should perform maintenance and repair of diving equipment, especially regulators, scuba cylinders, and other life support systems.

NOAA and other organizations have instituted a training and certification program for scuba cylinder inspectors. The objective of these programs is to ensure that uniform minimum inspection standards are used at diving facilities. People who successfully complete the course are certified as cylinder inspectors. The issuance of visual cylinder inspection stickers is tightly controlled.

The cylinder inspection course covers the following topics:

- Reasons for cylinder inspection;
- Frequency of inspection;
- Types of inspection;
- Analysis of cylinder structure and accessories;
- Criteria of inspection, e.g., wall thickness, material and valve specifications;
- Evaluation of cylinder interior and exterior;
- Use of inspection equipment, e.g., lights, probes, flushing solutions;
- Detailed inspection sequence (this is an 18-step process describing each step of a cylinder inspection); and
- The inspection of a minimum of 10 cylinders under the supervision of an instructor.

SECTION 8
WORKING DIVE PROCEDURES

WORKING DIVE PROCEDURES

8

8.0 GENERAL

This section describes some of the techniques and procedures used by scientific and academic divers engaged in routine underwater work operations. The diving mode of choice for underwater work that requires the diver to remain submerged for extended periods of time is supplied air. This mode is also called umbilical diving.

8.1 SURFACE-SUPPLIED DIVING PROCEDURES

The surface-supplied air diving mode is widely used by NOAA divers and by diver-scientists because it gives them the flexibility they need to perform many different underwater tasks. In surface-supplied diving, the diver's breathing mixture is supplied from the surface by means of a flexible hose; thus, divers using this mode have a continuous breathing gas supply.

The surface-supplied mode is generally used when divers need to remain under water for an extended period of time to accomplish the dive's objectives. The advantages of surface-supplied diving over scuba diving are that it:

- provides greater safety;
- permits dives to greater depths;
- permits divers to stay on the bottom for longer periods;
- provides thermal protection (if diving in cold water);
- permits communication between the diver and the surface; and
- provides an unlimited air supply.

Another advantage of the surface-supplied mode is that it can be undertaken using a variety of support platforms, including piers, small boats, barges, and ships. The disadvantages of this mode, compared with the scuba mode, are: (1) that the umbilical diver's mobility and operational range are restricted by the length of the umbilical; and (2) that a large amount of equipment is required to support umbilical diving.

Surface-supplied diving gear includes both deep-sea and lightweight equipment. When a diver-scientist needs maximum protection from the physical or thermal environment or when the dive is deep (i.e., to 190 fsw (57 m)), the deep-sea diving outfit shown in Figure 8-1 is the diving dress of choice. For dives to shallower depths that do not require maximum protection from pollution, temperature extremes, or underwater objects, a lightweight diving outfit may be used. (Section 5 describes diver and diving equipment of various types in detail.)

8.1.1 Planning the Dive

The success of any dive depends on careful pre-dive planning, which must consider the goals of the dive, the tasks involved in achieving these goals, environmental conditions (both surface and subsurface), the personnel needed to carry out the dive, the schedule for the dive, the equipment needed to conduct the dive safely and efficiently, and the availability of emergency assistance. Figure 8-2 is a checklist that can be used to evaluate environmental conditions that may affect the dive.

For every surface-supplied dive, the dive supervisor should complete this checklist (or one adapted to the specific conditions of a particular dive) before deciding on personnel and equipment needs. Different environmental conditions affect members of the dive team differently. For example, divers are generally not affected by surface waves except when entering or exiting the water; however, divers operating in very shallow waters, in surf, or in exceptionally large waves can be affected by wave action at the surface.

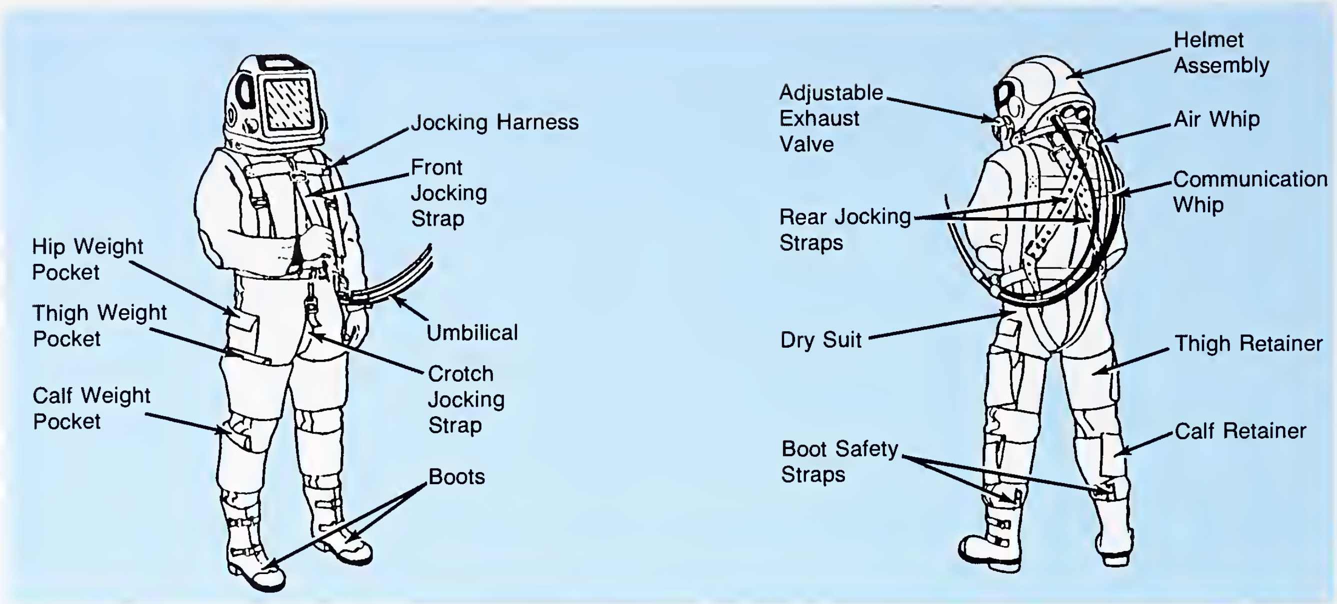
Air temperature and wind conditions at the surface also may have a greater effect on the tender and other surface support personnel than on the diver, because these individuals are more exposed than the diver to surface conditions. It is important to remember, however, that the surface crew should be able to operate with maximal efficiency throughout the dive, because reductions in the performance of topside personnel could endanger the diver.

Visibility at the surface can affect the performance and safety of the diver and the surface crew. For example, a diver surfacing under low- or no-visibility conditions might not be able to find the support craft.

The underwater environment can influence many aspects of a dive, from crew selection to choice of diving mode. All diving operations must consider:

- depth;
- bottom type;

Figure 8-1
Surface-Supplied Diver
in Deep-Sea Dress



Source: US Navy (1988)

- temperature of the water;
- underwater visibility; and
- tides and currents.

In addition, the presence of contaminants in the water (see Section 11), underwater obstacles, ice, or other unusual environmental conditions can affect planning for some dives.

Dive depth must be measured using two different methods before the dive begins. To obtain an accurate depth profile of the area of the dive, a series of depth measurements must be plotted. Methods of measuring depth that may be used include lead line sounding, pneumofathometer, high-resolution sonar, or ship-mounted fathometer. Depth readings on maps or charts are useful for general screening purposes but are not sufficiently accurate to be used to measure dive depths.

Samples should be taken of the bottom in the general area of the dive; in some instances, in-situ observations can be made before the dive. **Bottom conditions** affect a diver's mobility and visibility under water; a sandy bottom allows maximum mobility, and the diver's movements do not stir up so much sediment that visibility is restricted. By comparison, working in an area with a muddy and silty bottom can be dangerous, because the diver may become entrapped in the mud and usually generates sufficient silt to interfere substantially with visibility.

Currents must be considered in dive planning, whether the surface-supplied scientist-diver is working in a river or the ocean. The direction and velocity of river, ocean, and tidal currents vary with such factors as the time of year, phase of the tide, bottom conditions, depth, and weather.

Underwater visibility and **water temperature** also have a major influence on dive planning. For a detailed description of underwater conditions in major U.S. geographical regions, see Section 10.1.

8.1.2 Selecting the Dive Team

The size of the team needed for a surface-supplied dive depends on the number of divers on the dive team, the type of equipment available, the dive's safety requirements, environmental conditions, dive depth, dive mission, and the surface support platform available. The optimal number of dive team personnel for a large and complex surface-supplied dive is six: a dive supervisor, diver, standby diver, tender, standby tender, and timekeeper/recorder. If all members of the team are fully trained, a job rotation system can be used that permits all team members to take turns serving as divers; this approach allows for maximum in-water working time and is thus both logistically and economically efficient.

The **dive supervisor** is responsible for planning, organizing, and managing all dive operations; the dive supervisor remains at the surface at all times. This individual also determines equipment requirements, inspects the equipment before the dive, selects team members, ensures that emergency procedures and first aid supplies are available, conducts pre-dive briefings,

Figure 8-2
Predive Environmental
Checklist

Surface

Atmosphere

Visibility ____________
Sunrise/Set ____________
Moonrise/Set ____________
Temperature (air) ________
Humidity ____________
Barometer ____________
Precipitation ____________
Cloud Description/Cover ___
Wind Direction/Force _____
Other: ____________
____
____

Sea Surface

Sea State ____________
Wave Action:
Height ____________
Length ____________
Direction ____________
Current:
Direction ____________
Velocity ____________
Type ____________
Visibility ____________
Water Temperature ____
Local Characteristics ___

Subsurface

Underwater and Bottom

Depth ____________
Water Temperature:
_____ degrees at _____ depth
_____ degrees at _____ depth
_____ degrees at _____ depth
_____ degrees at bottom

Thermoclines:
at _________ depth
at _________ depth
Current:
Direction
Source
Velocity
Pattern
Tides:
High Water ____/____ time
Low Water ____/____ time
Ebb Direction __ Velocity __
Flood Direction __ Velocity __

Visibility

Underwater:
_____ feet at _____ depth
_____ feet at _____ depth
_____ feet at _____ depth
Bottom
_____ feet at _____ depth

Bottom Type:
____
Obstructions:
____
____
Marine Life:
____
____
Other:
____
____

Adapted from US Navy (1988)

monitors the progress of the dive, debriefs the divers, prepares reports of the dive, and checks equipment and diver logs at the completion of the dive.

The **diver**(s) must be qualified and trained in the equipment and diving techniques needed for the dive. During the course of the dive, the diver must keep surface personnel informed of the progress of the dive, bottom conditions, and any problems (actual or potential). Every diver is responsible for ensuring that his or her diving gear is complete, in good repair, and ready for use. In addition, all divers must know both line pull signals and voice signals and must respond to and comply with instructions from surface personnel.

The **standby diver** must be as well trained and qualified as the diver; a standby is required for all surface-supplied operations, regardless of size. It is the responsibility of the standby diver to be ready to provide emergency or backup support to the diver any time the diver is in the water.

The **tender** is the member of the surface team who is responsible for tending the diver while the diver is in the water. Every diver in the water must have a tender. Before the diver enters the water, the tender:

- checks the diver's equipment;
- checks the air supply; and
- dresses the diver.

Once the diver is in the water, the tender takes care of the diver's lines to ensure that no excess slack or tension is on the line. In addition, the tender maintains communication with the diver and keeps the diving supervisor informed of the diver's progress. All tenders should be fully qualified divers.

On complex dives, a **standby tender** may be needed. The standby tender should be fully trained as a diver and should be instructed in all of the required duties of the tender. It is the standby tender's job to be ready to assist the tender or to replace him or her at any time.

The **timekeeper** may be dedicated to keeping the diver's time during the job or, on dives involving a limited number of dive team members, the tender may also serve as the timekeeper. The timekeeper's responsibilities involve keeping an accurate record of dive times and noting all of the important details of the dive. On some dives, the dive supervisor acts as the timekeeper.

8.1.3 Dressing the Surface-Supplied Diver

Surface-supplied divers use either a diving mask or a helmet, and the supervisor and diver must decide whether a dry suit, wet suit, or bathing suit is appropriate for a particular dive. Factors to be considered when making these choices include:

- Personal preference;
- Depth of the planned dive;
- Nature of the work to be performed;
- Length of the planned dive;
- Environmental conditions (temperature of the water, speed of current, underwater visibility, etc.); and
- Condition of the water, i.e., polluted or clean.

The dressing procedures followed by the diver and his or her tender depend on the type of dress selected for the dive.

At least one tender assists in dressing a diver wearing a lightweight surface-supplied diving system (dry suit) or a wet suit. If a dry suit is to be worn, the diver applies a lubricant to the suit's zipper and then, while seated, inserts his or her legs into the suit. The diver then stands and works both arms into the suit's sleeves. The tender holds the breech ring while the diver is performing these procedures. Then the tender:

- Wraps the harness chest strap tab around the left shoulder strap and presses it into place;
- Pulls the crotch strap to the front and fastens the weight belt latch;
- Adjusts the waist belt and shoulder straps and secures both rear jocking straps;
- Inserts thigh and calf weights and secures the thigh and calf restrainers;
- Ensures that air is available to the helmet and that the air supply valve is opened;
- Lowers the helmet into place on the diver's head and aligns it with the lower breech ring lugs;
- Presses the quick-release locking pins, slides them into place, and ensures that all pins are locked;
- Positions the umbilical and whips under the diver's left arm and secures them;
- Performs a communications check; and
- Establishes the appropriate air flow.

If a lightweight mask (Figure 8-3) is to be used with a wet suit or bathing suit, dressing procedures are simpler than those described above. For divers wearing a wet suit or a bathing suit, the tender assists the diver to perform the following steps:

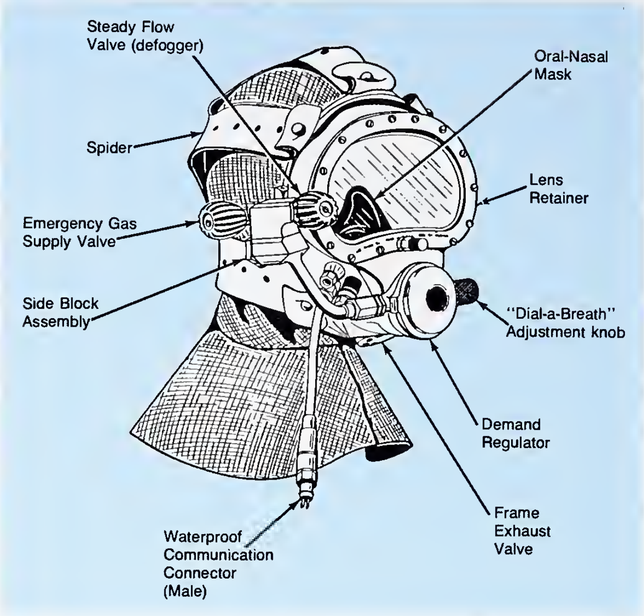
- Don the harness;
- Place the lower breech ring with neck dam over the diver's head;
- Secure the ring to the jock strap; and
- Place the helmet on the diver's head and secure it.

Figure 8-4 shows a surface-supplied diver dressed and ready to dive in a wet suit.

8.1.4 Tending the Surface-Supplied Diver

The tender is the dive team member in closest communication with the diver during the dive. Before the dive begins, the tender checks the diver's diving dress, paying particular attention to the valves on the helmet, the helmet locking device, the helmet seal, and the harness. The tender then dresses the diver and helps the diver to position himself or herself on the diving stage or ladder. The tender must always keep a hand on the diver's lifeline close to the helmet to steady the diver and to prevent a fall.

Figure 8-3
Lightweight Surface-Supplied Mask



Source: US Navy (1988)

As the diver enters the water, the tender pays out the umbilical at a steady rate, being careful to avoid sharp edges. Throughout the dive, the tender must keep slack out of the line; at the same time, the tender must be careful not to pull the line taut. Maintaining approximately 2 or 3 feet (0.7 to 1 m) of slack on the line permits the diver the right degree of freedom and prevents him or her from being pulled off the bottom by currents or by the movement of the support craft. Too much slack in the line interferes with effective line communication between the diver and tender and increases the likelihood of line fouling.

Throughout the dive, the tender continuously observes the descent line and monitors the umbilical to receive any line-pull signals from the diver. If an intercom system is not in use, the tender periodically signals the diver (using line pulls) to ensure that the diver's condition is good. If the diver fails to respond to two pull signals, the situation must be treated as an emergency and the dive supervisor must be notified immediately.

8.1.5 The Dive

Once the diver is dressed and ready for the dive, the tender helps the diver to prepare for water entry. The entry technique used depends on the staging area or type of vessel involved in the operation. If a stage is used for diver entry, the diver should stand or sit squarely

Figure 8-4
Surface-Supplied Diver
In Lightweight Mask
and Wet Suit

Source: US Navy (1988)

on the stage platform and maintain a good grip on the rails. If the diver makes a jump or roll entry into the water, he or she must maintain a grip on the face mask while the tender maintains sufficient slack on the line and air hose.

When the diver is positioned for descent, the following procedures, as appropriate, should be followed by various members of the dive team.

- The diver should adjust his or her buoyancy, if necessary. Whether the diver is weighted neutrally or negatively will depend on the dive's objectives.
- The tender should re-verify that the air supply system, helmet (or mask), and communications are functioning properly. If not, corrections must be made before the diver's descent. The tender should check for any leaks in the air supply fittings or suit and also should look for air bubbles. No diver should dive with malfunctioning equipment.
- The tender should also re-verify that all equipment is functioning satisfactorily.
- The diving supervisor should give the diver permission to descend.
- The diver should descend down a descent or "shot" line. The descent rate used depends on the diver; however, it should not exceed 75 ft/min (22.9 m/min). The air supply should be adjusted for breathing ease and comfort.
- The diver must equalize pressure in both ears and sinuses during descent. If equalization is not possible, the dive must be terminated.
- When descending in a tideway or current, the diver should keep his or her back to the current so that he or she will be forced against the descent line.
- When the diver reaches the bottom, the tender should be informed of the diver's status and the diver should ensure that the umbilical assembly is not fouled in the descent line.
- If necessary, buoyancy and air flow should be regulated before releasing the descent line; adjustments to air control valves should be made in small, cautious increments.
- The diver should attach a distance line (if one is used) and should then proceed to the work area. A distance line should be used when visibility is extremely poor and the diver cannot see the descent line from a distance.
- After leaving the descent line, the diver should proceed slowly to conserve energy. It is advisable for divers to carry one turn of the umbilical hose in the hand.
- The diver should pass over, not under, wreckage and obstructions.
- If moving against a current, it may be necessary for the diver to assume a crawling position.
- If the diver is required to enter wreckage, tunnels, etc., a second diver should be on the bottom to tend the umbilical hose at the entrance to the confined space.
- The tender must constantly inform the diver of the bottom time. The diver should be notified a few minutes in advance of termination so that the task can be completed and preparations made for ascent.

If the diver experiences rapid breathing, panting, or shortness of breath, abnormal perspiration, or an unusual sensation of warmth, dizziness, or fuzzy vision, or the helmet ports have become cloudy, there is probably an excess of carbon dioxide in the helmet. To get rid of this excess, the air flow in the helmet should be increased immediately by simultaneously opening the air control and exhaust valves.

8.1.5.1 Diver Emergencies

Fouling

A surface-supplied diver's umbilical may become fouled in mooring lines, wreckage, or underwater structures, or the diver may be trapped by the cave-in of a tunnel or the shifting of heavy objects under water. In such emergencies, surface-supplied divers are in a better position to survive than scuba divers, because they have a virtually unlimited air supply and can communicate with the surface, both of which facilitate rescue operations. Fouling may result in fatigue, exposure, and prolonged submergence, and it may also necessitate an extended decompression. Divers who are fouled should:

- Remain calm;
- Think clearly;
- Describe the situation to the tender;
- Determine the cause of fouling and, if possible, clear themselves; and
- Be careful to avoid cutting portions of their umbilical assembly when using their knife.

If efforts to clear themselves are unsuccessful, divers should call for the standby diver and then wait calmly for his or her arrival. Struggling and other panicky actions only make the situation worse by using up the remaining air supply at a faster rate.

Blowup

Blowup is the uncontrolled ascent of a diver from depth; this is a hazard for divers using either a closed dress (deep-sea or lightweight helmet connected to a dry suit) or variable-volume dry suit (UNISUIT® or equivalent). Blowup occurs when the diving dress or suit becomes overinflated or the diver loses hold of the bottom or descending line and is swept to the surface. During blowup, the diver exceeds the rate of ascent (25 ft/min (8 m/min)) that must be maintained to be decompressed successfully at the surface. Accidental inversion of the diver, which causes the legs of the suit to fill with air, also may result in uncontrolled blowup. Accidental blowup can cause:

- Cerebral gas embolism;
- Decompression sickness; and/or
- Physical injury (if the diver's head strikes an object, such as the bottom of a ship or platform).

Before descending, the diver must be certain that all exhaust valves are functioning properly. The diving suit or dress should fit the diver well to avoid leaving excessive space in the legs in which air can accumulate; air in the legs of the suit presents a serious hazard, particularly with variable-volume suits. Divers must be trained under controlled conditions, preferably in a swimming pool, in the use of all closed-type diving suits, regardless of their previous experience with other types of suits. Some divers have attempted to use a technique called "controlled blowup" for ascent; however, this method of ascent should never be used because losing control of the rate of ascent can have fatal consequences.

After surfacing, blowup victims should not be allowed to resume diving. If a diver who has experienced a blowup appears to have no ill effects and is still within the no-decompression range prescribed by the tables, he or she should return to a depth of 10 feet (3.0 m) and decompress for the amount of time that would normally have been required for ascent from the dive's working depth. The diver should then surface and dress, after which he or she should be observed for at least an hour for signs of delayed-onset air embolism or decompression sickness.

Blowup victims who are close to the no-decompression limit or who require decompression should first be recompressed in a chamber and then be decompressed in accordance with surface decompression procedures; if the available surface decompression tables are not adequate, the victim should be recompressed in a chamber to 100 feet (30.5 m) for 30 minutes and then be treated in accordance with U.S. Navy Treatment Table 1A (see Appendix C). If no chamber is available, conscious victims should be treated in accordance with recompression procedures for interrupted or omitted decompression; unconscious victims should be handled according to the recompression table in Appendix C that is designed for cases of air embolism or serious decompression sickness.

Loss of Primary Air Supply

Although losing the primary air supply is an infrequent occurrence in surface-supplied diving, it does occasionally occur. In the event of a primary air supply malfunction or loss, the panel operator should switch immediately to the secondary supply, notify the tender and diver, and call for the termination of the dive. (Secondary air supply systems on the surface are discussed in Sections 4.2 and 14.5 for both air compressor and high-pressure cylinder air supplies.)

The use of self-contained emergency air supplies in surface-supplied diving has significantly reduced the hazard associated with primary air supply failure. In an emergency, a diver equipped with such a supply can simply activate his or her emergency supply and proceed to the surface. Divers faced with the loss of their surface supply should close their helmet free-flow valves to conserve air, and the surface crew should be alerted to the situation as soon as it develops. If, because of fouling, the diver is forced to cut the air supply line, a check valve incorporated into the reserve manifold will prevent loss of the reserve air supply. The diver must immediately terminate the dive if it is necessary to switch to the emergency supply; under no conditions should the diver attempt to complete the work task.

If the primary air supply fails when a diver is diving without a self-contained emergency air supply, the diver can drop his or her weight belt (without removing the mask) and then ascend to the surface, exhaling throughout the ascent to prevent air embolism. A diver with a fouled hose should release his or her weight belt and harness (or harness attachment) and then remove the mask by grasping it and pulling it forward, up, and over the head. The surface-support team should handle a diver who surfaces in this way in the same manner as a blowup emergency, because air embolism or decompression sickness is a possibility.

Loss of Communication or Contact with the Diver

If contact with the diver is lost, the following procedures should be implemented:

- If intercom communication is lost, the tender should immediately attempt to communicate with the diver by line-pull signals (see Section 14.2).
- Depending on diving conditions and the arrangements made during dive planning, the dive may either be terminated or continued to completion (using line-pull signals for communication). In research diving, it is generally best to terminate the dive so that the problem can be resolved and the dive plan revised.
- If the tender does not receive an immediate line-pull signal reply from the diver, greater strain should be taken on the line and the signal should be sent again. Considerable resistance to the tender's pull may indicate that the umbilical line is fouled, in which case a standby diver should be dispatched as soon as possible.
- If the tender feels sufficient tension on the line to conclude that it is still attached to the diver but continues to receive no reply to line-pull signals, the diver should be assumed to be unconscious. In this event, the standby diver should be dispatched immediately.
- If no standby diver is available, or if for some reason it is considered unwise to use one, the diver must be pulled to the surface at a rate of 60 feet (18.3 m) per minute or less, and the tender and the dive team should be prepared to administer first aid and recompression as soon as the diver surfaces. If the diver is wearing closed dress or a variable-volume dry suit, pulling him or her to the surface is likely to cause blowup unless another diver is available to assist with the ascent. It is thus essential that a standby diver be ready at all times to enter the water when divers wearing variable-volume dry suits are in the water.

Loss From View of Descent or Distance Line

Occasionally a diver will lose sight of the descent line or lose contact with the distance line. If the distance line is lost, the diver should search carefully within arm's reach or within his or her immediate vicinity. If the water is less than 40 feet (12.2 m) deep, the tender should be informed and should haul in the umbilical assembly and attempt to guide the diver back to the descending line. In this situation, the diver may be hauled a short distance off the bottom. When contact with the descent line is regained, the diver should signal the tender to be lowered to the bottom again. In water deeper than 40 feet (12.2 m), the tender should guide the diver to the descent line in a systematic fashion.

Falling

Falling is an especially serious hazard for divers using deep-sea or helmet equipment to work on the hull of a ship. A diver falling off a diving stage or work platform wearing such equipment is much more likely to be injured than a diver falling a greater distance in open water. The principal danger from falling is the sudden increase in pressure, which may not be compensated for by the overbottom pressure of the air supply; this could result in helmet or mask squeeze. The diver and tender must therefore always be alert to the possibility of a fall. Should the diver start to fall, the tender should take an immediate strain on the umbilical assembly to steady the diver.

The likelihood of a faceplate being cracked during a fall when a modern helmet is being used is relatively small. If the faceplate does crack, however, the diver should continue to wear it, and the air pressure should be increased slightly to prevent water leakage.

If a tear develops in a variable-volume suit, the dive should be terminated immediately because the chilling effect of water entering the suit can be severely debilitating to a diver. If a closed suit with the helmet attached is torn in a fall, the diver should remain in an upright position and ascend to the surface at a safe rate of ascent.

8.1.6 Ascent

When the diver's bottom time has expired or the task has been completed, the diver should return to the ascent line and signal the tender to prepare for ascent. The following procedures should be used;

- The tender should pull in any excess umbilical line and exert a slight strain on the line; he or she should then exert a slow and steady pull at the prescribed rate (generally 60 ft/min (18.3 m/min));

- The tender should start a timer on the surface and should then monitor this timer (along with the pneumofathometer) to control the diver's ascent rate;
- The diver controls his or her buoyancy by using either a buoyancy compensator or adjusting the air in his or her closed- or variable-volume suit (the diver must be careful not to overinflate the suit, which could cause an accidental blowup);
- The diver should continuously hold onto the line during ascent;
- The tender or diving supervisor should inform the diver well in advance of his or her decompression requirements (a diving stage may be required for long decompressions);
- When decompression is completed, the tender assists the diver to board the support platform.

8.1.7 Post-Dive Procedures

Divers should be helped from the water and should then be assisted by surface-support personnel in removing their equipment. The following procedures are recommended:

- Remove the weight belt;
- Remove the helmet and secure the air flow valve;
- Unbuckle and remove the emergency backpack;
- Remove the neckring assembly;
- Unbuckle and remove the jocking belt.

If the diving system is not to be used again that day:

- Close the supply valve and vent the primary air hose;
- Close the emergency air cylinder valve, open the reserve air valve to vent the line, and close the reserve air valve again;
- Disconnect the primary air hose from the emergency manifold;
- Disconnect the hose from the helmet inlet and disconnect the communication cable;
- Place the helmet in an upright position, rinse external surfaces with fresh water, and wipe them dry; clean the interior, if necessary, with a damp sponge and then wipe it dry;
- Rinse the jocking belt in fresh water and hang it up to dry.

The divers should be observed for any signs of sickness or injury caused by the dive, and warming procedures should be commenced as soon as possible if the divers are chilled. The divers and tenders should report any equipment defects noted during or after the dive, and defective equipment should be tagged for corrective maintenance. The divers should then be debriefed and the log completed. Divers should establish their own standard of care for their masks, depending on the conditions of use. For example, using a mask in fresh water requires different maintenance procedures and cleaning frequencies than are required when a mask is used in seawater. The type of underwater activity also influences maintenance requirements. When diving in seawater, the exterior of the mask should be rinsed in fresh water after each dive, taking care not to flood the microphones. The interior of the mask should then be wiped clean with a cloth or sponge. An alcohol solution is useful for cleaning and disinfecting the oral-nasal mask. (Inhibisol® or similar solvents should not be used, because they will harm the acrylic port.) The interior of the mask should be completely dry when the mask is stored, even if the storage time is very short. Some masks should be placed in the face-down position to allow water to drain from the face seal.

Masks of some types require additional maintenance. For example, the interior of masks that are fitted with a cold-water hood are difficult to clean and dry unless the hood is first removed. After the hood is removed, the mask should be turned inside out and the water in the open-cell foam face seal should be squeezed out. The interior of the hood and mask should be dried completely before reassembling. Installing a zipper in the back of the hood simplifies maintenance because it reduces the number of times the hood has to be removed. Monthly (or between-dive) maintenance and repair should be performed on all masks in accordance with the manufacturer's instructions and the service manual supplied with each mask.

8.1.8 Umbilical Diving From Small Boats

Although most surface-based umbilical diving is conducted from large vessels or fixed platforms, the umbilical system can be adapted readily to small boat operations. When working from small boats, i.e., at depths of 16 to 30 feet (4.9-9.1 m), a bank of high-pressure cylinders is usually used to supply breathing air, which enables the team to operate without an air compressor and its accompanying bulk and noise. The number and size of the high-pressure cylinders required depend on the size of the boat and on operational requirements. For small boats, two or more sets of standard twin-cylinder scuba tanks can be connected by a specially constructed manifold that is, in turn, connected to a high-pressure reduction regulator or small gas control panel. The umbilical is then connected to the pressure side of the pressure reduction unit. In larger boats, air may be carried in a series of 240- or 300-cubic foot (6.8 or 8.5 m^3) high-pressure cylinders. Regardless of the cylinder configuration used, all cylinders must be secured properly, and the valves, manifold, and regulator must be protected to prevent personnel and equipment damage. The umbilical may be coiled on top of the air cylinders or in the bottom of the boat. For the convenience of the tender, the communicator is generally placed on a seat or platform. Communications equipment must be protected from weather and spray. Because small boats can only be used to support shallow water work, the umbilical from the boat to the diver is usually 100 to 150 feet (30.5-45.7 m) in length. It is generally wise to limit diving depths to less than 100 feet (30.5 m) when working from a small boat.

The diving team for a surface-supplied dive from a small boat usually consists of a diver, tender, and standby diver. The tender, who is a qualified diver, also serves as the supervisor on such dives. If properly qualified, all personnel can alternate tasks to achieve maximum operational efficiency. The standby diver may be equipped with a second umbilical and mask or, as is frequently the case, be equipped with scuba; he or she should be completely dressed and capable of donning scuba and entering the water in less than a minute. A standby using scuba should be fitted with a quick-release lifeline (readily releasable in the event of entanglement). Some divers use a heavy-duty communication cable as a lifeline, which allows the standby diver and tender to stay in communication. This line is also constructed so that it may be released readily in case of entanglement.

Many divers consider high-pressure cylinder air supply systems safer and more dependable than systems incorporating a small compressor and a volume or receiver tank, and some divers prefer to have a small tank incorporated into the system to provide air for surfacing in an emergency. Most experts agree that a diver should carry a small self-contained emergency scuba tank for use in the event of primary system failure. An emergency supply of this type is mandatory when a diver will be working around obstructions or inside submerged structures.

8.1.9 Basic Air Supply Systems

The two basic types of air supply systems used for surface-supplied diving are:

- Air compressors; and
- High-pressure cylinder systems.

When properly configured, either of these air sources is able to supply breathing gas that is:

- Of specified purity (see Table 15-3);
- Of adequate volume;
- At the proper pressure; and
- Delivered at a sufficient flow rate to ensure adequate ventilation. Regardless of the type of system, it is imperative that it be in good repair, be serviced at regular intervals, and be manned by trained personnel.

Air compressors are discussed in more detail in Section 4.2. When the air supply system for surface-supplied diving operations incorporates an on-line air compressor, the general system configuration is similar to that shown in Figure 8-5. When surface-supplied diving operations utilize a high-pressure cylinder system for diver air supply, the general system configuration used is the one shown in Figure 8-6.

8.1.10 Rates of Air Flow

The rate at which air must flow from the air supply to the diver depends on whether the breathing apparatus (helmet or mask) is operated in a free-flow or demand mode. With free-flow equipment, the primary requirement of the air supply system is that it have a capacity (in acfm) that will provide sufficient ventilation at depth to prevent the carbon dioxide level in the mask or helmet from exceeding safe limits at normal work levels and during extremely hard work or emergencies. By ensuring that the apparatus is capable of supplying at least 6 acfm (170 liters) under all circumstances, divers can be reasonably certain that the inspired carbon dioxide will not exceed 2 percent. To compute the ventilation rate necessary to control the level of inspired CO_2, the following equation should be used:

$$R = 6(Pa)\ (N)$$

where R = ventilation flow rate in scfm; Pa = absolute pressure at working depth in ATA; N = number of divers to be supplied.

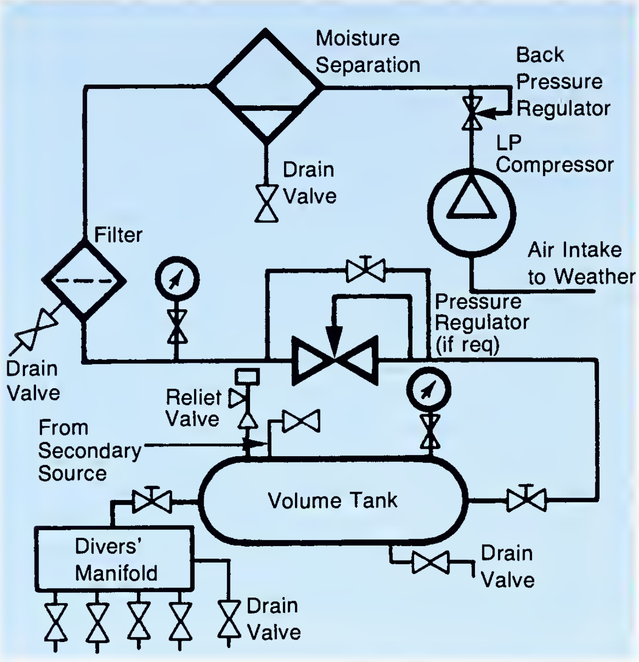
Example:

What ventilation rate would be required for two divers using lightweight helmets at 80 fsw (24.4 m)?

$$R = 6(Pa)(N)$$
$$R = 6(3.42)(2)$$
$$R = 41.04 \text{ scfm}$$

For demand equipment, the air requirement for respiration is based on the maximum instantaneous (peak) flow rate under severe work conditions. The maximum

Figure 8-5
Major Components of a Low-Pressure Compressor-Equipped Air Supply System



Source: US Navy (1985)

instantaneous flow is not a continuous demand but rather the highest rate of air flow attained during the inhalation part of the breathing cycle. A diver's air requirement varies with the respiratory demands of the work level. Consequently, the rate at which compressed air is consumed in the system is significantly lower than the peak inhalation flow rate.

Computing the rate of flow that the air supply system must be able to deliver for demand breathing equipment is essentially the same as calculating the consumption rate at depth (see Section 14.3).

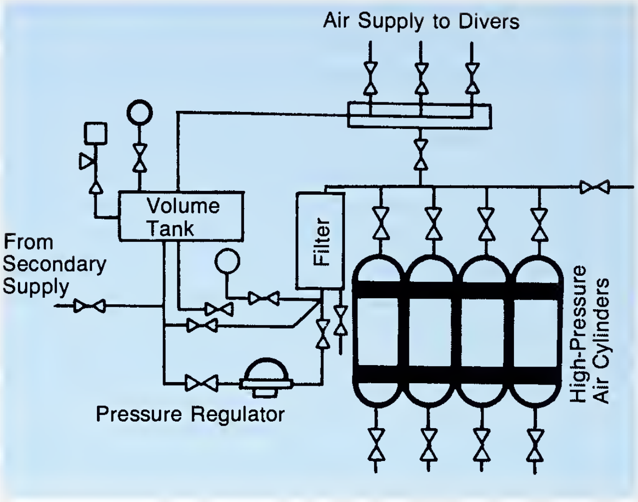
Example:

What rate of flow will a diver require using a demand mask and doing moderate work at 75 fsw (22.9 m)?

$$\begin{aligned} Cd &= \text{RMV (Pa)} \\ Cd &= (1.1 \text{ acfm})(3.27 \text{ ATA}) \\ Cd &= 3.6 \text{ scfm} \end{aligned}$$

For demand equipment, the rate of air flow must meet or exceed the diver's consumption rate at depth.

Figure 8-6
Typical High-Pressure Cylinder Bank Air Supply System



Source: US Navy (1985)

8.1.11 Supply Pressures

The air supply system must be capable at all times of delivering air to the diver at a pressure that overcomes the water pressure at the working depth (overbottom pressure) and the pressure losses that are inherent in any surface-supplied diving system (hoses, valves, and regulators). The supply pressure must always exceed the ambient pressure at the working depth to provide a safety factor in case an accidental rapid descent from below the planned working depth must be made.

When using a free-flow mask or lightweight helmet, a hose pressure of at least 50 psi is required for dives in water less than 120 fsw (36.6 m) in depth, and a pressure 100 psi greater than ambient pressure is necessary for depths exceeding 120 fsw (36.6 m). In addition, a loss through the valves of at least 10 psig should be anticipated. Simple calculations give the supply pressures necessary for most free-flow masks and lightweight helmets.

For depths less than 120 fsw (36.6 m):

$$P_S = 0.445D + 65 + P_i$$

where P_S = supply air pressure in psig; D = depth in fsw; 65 = absolute hose pressure (50 psi + 14.7 psi); and P_i = pressure loss in system.

For depths greater than 120 fsw (36.6 m):

$$P_S = 0.445D + 115 + P_i$$

where 115 = absolute hose pressure (100 psi + 14.7 psi).

8.2 SEARCH AND RECOVERY

Search techniques all rely on one common element: the adoption and execution of a defined search pattern. The pattern should commence at a known point, cover a known area, and terminate at a known end point.

Search patterns are implemented by carrying out search sweeps that overlap. To be efficient, the overlap should be minimal. The initial step in a search is to define the general area and the limits to be searched. If the search is being conducted to locate a specific object, the last known position of the object is the starting point for defining the search area. The drift in the open sea resulting from sea and wind currents, the local wind condition at the time the object was lost, and the leeway (movement through the water from the force of the wind) should be studied. Sea currents can be estimated for a particular area using current NOAA *Tidal Current Tables* and *Tidal Current Charts* and the U.S. Navy's current *Atlas of Surface Currents.* Wind currents can be estimated using Table 8-1.

The leeway generally is calculated at 0 to 10 percent of the wind speed, depending on the area of the object exposed to the wind and the relative resistance of the object to sinking. The direction of leeway is downwind, except for boats that have a tendency to drift up to 40 percent off the wind vector. Calculation of the value and direction of leeway is highly subjective for objects that float or resist sinking; however, if the average wind velocity is relatively low (under 5 knots (2.5 m/s)), or the object is heavy enough to sink rapidly, the leeway has little or no effect on the calculation of a probable location.

After the vectors of water current, wind current, and leeway have been added vectorially and applied to the last known position of the object, a datum point is defined. The datum point is the most probable position of the object. Once the datum point has been defined, the search radius around the datum point is selected. The search radius, R, is equal to the total probable error of position plus a safety factor, as defined by the following formula:

R = radius
k = safety factor (between 0 .1 and 1.5)
C = total probable error

where

$$R = (1 + k)\,C$$

The total probable error is a mathematical combination of the initial error of the object's position (x), the navigation error of the search craft (y), and the drift error (d_e). The drift error is assumed to be one-eighth of the total drift. The total probable error, C, is:

$$C = (d_e{}^2+x^2+y^2)^{1/2}$$

Each factor included in the total probable error is somewhat subjective. Selecting conservative values has the effect of enlarging the search radius; sometimes, a small search radius is selected, and repeated expansions are made around the datum point until the object is located. Searching the area around the datum point can be implemented using a variety of patterns, depending on the search equipment, visibility, or number of search vehicles involved.

Table 8-1
Wind Speed and Current Estimations

Wind Speed, knots (m/s)	Wind Current, miles/day (km)
1-3 (0.5- 1.5)	2 (3.2)
4-6 (2.0- 3.0)	4 (6.4)
7-10 (3.5- 5.0)	7 (11.3)
11-16 (5.5- 8.0)	11 (17.7)
17-21 (8.5-10.5)	16 (25.8)
22-27 (11.0-13.5)	21 (33.9)
28-33 (14.0-16.5)	26 (41.9)

Adapted from NOAA (1979)

Systematic searching is the key to success. A good search technique ensures complete coverage of the area, clearly defines areas already searched, and identifies areas remaining to be searched. The visibility, bottom topography, number of available divers, and size of the object(s) to be located are prime factors in selecting the best method for a particular search.

There are two **acoustic approaches** to underwater object location. The first is to traverse the area being searched with a **narrow beam fathometer,** keeping track of the ship's position by normal surface survey methods. This approach is suitable for returning to the position of a known object that has high acoustic relief and is located in an otherwise relatively flat area, such as a wreck, significant rock outcrop, or a mount. The second acoustic method involves the use of **side-scan sonar**. When using side-scan sonar, a transponder receiver unit is towed either from the surface or a submersible. Acoustic beams are broadcast left and right, and the signals received are processed to present a picture of the bottom on both sides of the transponder-receiver unit. Approximate object position can be determined by knowing the ship's position, heading, and speed, and the approximate position of the transponder-receiver unit with respect to the ship.

Onboard microprocessors to control the range/gain necessary to produce optimum display contrast are beginning to replace manual adjustment of the gain; the use of microprocessors simplifies the task of the observer and increases the effectiveness of a search. If more precise determination is necessary, one of the acoustic surveying methods described in Section 9.1.3 can be used. Underwater object location using acoustic techniques involves divers only after the object has been detected. The following diver search techniques have been useful for such purposes.

8.2.1 Circular Search

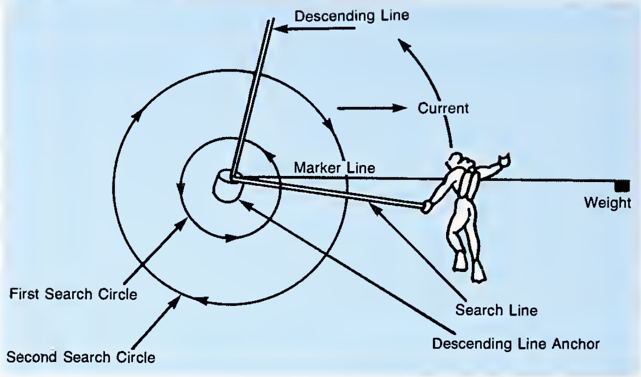
In conditions where the bottom is free of projections, the visibility is good, the object to be located is reasonably large, and the area to be searched is small, use of the **circular search technique** is recommended. Under such favorable conditions, a floating search line is anchored to the bottom or tied with a bowline around the bottom of the descent line and is used to sweep the area. To determine when a 360-degree circle has been made, a marker line should also be laid out from the same anchor as the search line. This marker line should be highly visible and should be numbered with the radial distance from the anchor.

Where current is noticeable, the marker line should be placed in the downcurrent position so that the diver always commences the search from the position having the least potential for entanglement. When more than one circle is to be made with tethered divers, the direction of travel should be changed at the end of each rotation to prevent the possibility of fouling lines.

The circular search has many modifications, depending on the number of divers and the thoroughness required. The standard technique is to station one or more divers along the search line close to the center of the search area. The marker line can be used to assign precise distances. The divers hold the search line and swim in a circle until they return to the marker line, which ensures that a full 360 degrees has been covered. The divers increase the radius for the next search, moving out a distance that permits good visual coverage. This procedure is continued until the outermost perimeter is reached (see Figure 8-7).

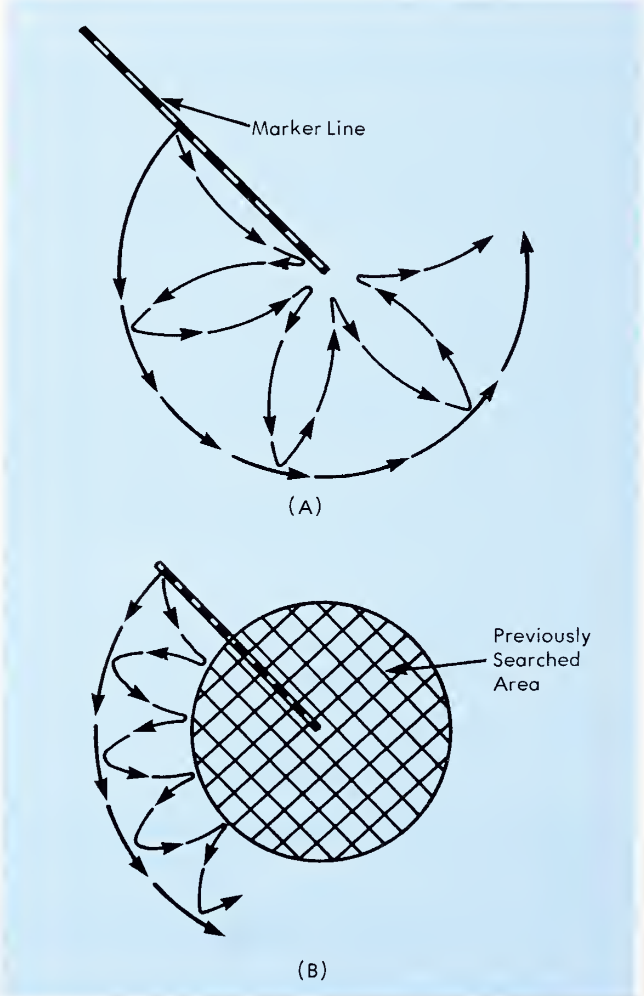
When two divers are searching, search effectiveness can be increased by having one diver hold the circling line taut and swim the outside perimeter of the area to be searched while another diver sweeps back and forth along the taut circling line. As shown in Figure 8-8A, the first search will cover a full circle bounded by the outside diver's path. The search starts and finishes at the marker line. The search may be extended by the pattern shown in Figure 8-8B, in which case the circling line is marked at the point where the outside diver was previously stationed. The outside diver then moves to a new position, farther out on the circling line, and the inside diver sweeps back and forth between the marker and the outside diver's new position. Positions may be changed at regular intervals if the divers become fatigued. Changing positions can be done at the end of each sweep by having the outside diver hold

Figure 8-7
Circular Search Pattern



Courtesy *Skin Diver* Magazine

Figure 8-8
Circular Search Pattern for Two Diver/Searchers



Source: NOAA (1979)

position after moving out one visibility length; the other diver then moves outside, taking up his or her position for the next sweep. If the search is conducted in murky water, using a weighted line may be advisable; if the lost object is shaped so that it will snag the moving line, a pull on the line will tell the diver that the object has been found.

Circular search techniques also may be used for diving through the ice in waters that have no current, such as inland lakes and quarries. The following procedure has been used successfully by the Michigan State Police Underwater Recovery Unit (1978). When the ice is covered with snow, a circle is formed in the snow, using the under-ice entry hole as the center pivot point. The radius of the circle is determined by the length of line used to tend the diver. The circle on the snow indicates the area being searched and the approximate location of the diver who is searching under the ice. If the object of the search is not recovered within the first marked-off area, a second circle that slightly overlaps the last circle is formed on the surface. This procedure is continued until the complete area has been searched. The circular pattern involves only one diver, with a backup diver standing by; before entering the hole, the diver is secured by one end of the line, and the other end is held by the tender. The diver in search of an object will go directly below the hole and make a search of the immediate area. If the object is not found directly below, the diver returns to the surface and describes the underwater conditions. The diver then proceeds just under the ice to the full length of the line (approximately 75 feet (25 m)). With the use of rope signals, the diver begins circling, keeping the line taut and staying about 6 or 8 inches (15-20 cm) below the ice. After the diver completes one circle without encountering any resistance, the tender signals the diver to descend to the bottom. With the line taut, the diver begins the first circle on the bottom.

After the diver completes one circle, the tender signals the diver and pulls him or her to a new location (within the limits of visibility). The diver commences searching in a second circle, and the pattern is repeated until the diver again reaches the hole. If the diver's physical condition continues to be satisfactory, a second hole is cut in the ice and the procedure is repeated; otherwise, the standby diver takes over and a second standby diver is designated. Figure 8-9 illustrates this through-the-ice search technique.

8.2.2 Arc Pattern (Fishtail) Search

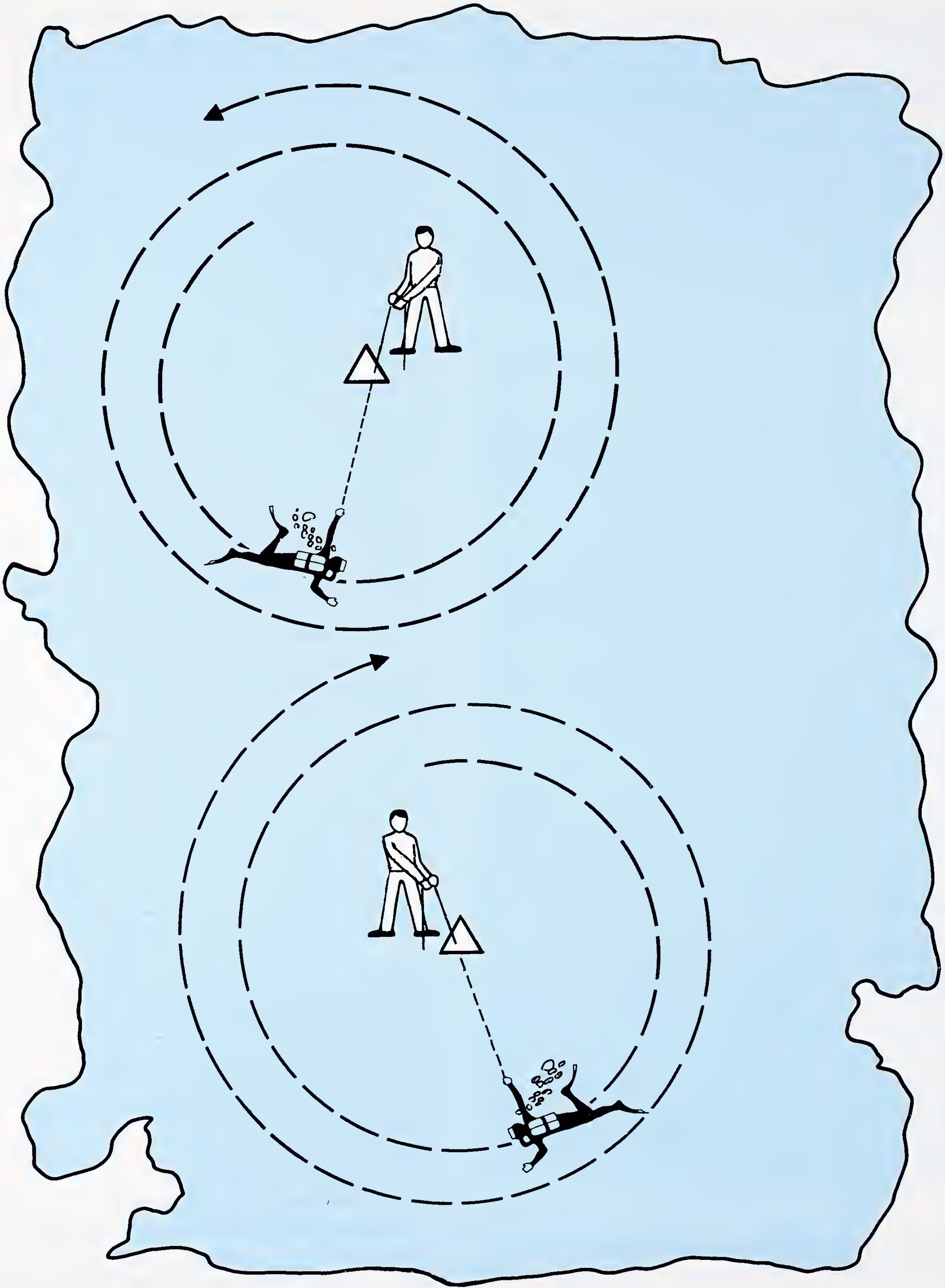
The arc pattern search technique is used to perform an under-ice search in water that has a current. The diver is secured with a descending line in the same manner described above for a circular search. The diver descends to the bottom (using a weighted line, if necessary) and searches the immediate area. After reporting to the surface, the diver again descends, going downstream to the extended length of the line. At this point, the diver begins moving sideways in an arc-type swing. As the diver circles in the pattern, he or she will feel some resistance on the upward swing of the arc. When this occurs, the diver signals the tender, who pulls in the line the distance of the diver's visibility. The diver then swings back along the bottom in the opposite direction until he or she again meets the resistance of the current. The pattern is repeated until the diver is back at the original starting point. This pattern can also be used in open water, including rivers and lakes, and can be conducted from bridges, boats, and off the shore. The fishtail technique is shown in Figure 8-10.

A variation on the arc pattern search can be used to relocate objects in waters with fast-moving currents. After reaching the general vicinity of the object, the diver searches large areas of the river bottom by swinging in widening arcs from a line attached to a heavy pivotal object, such as an anchor, a stake driven into the bottom, or a creeper. The diver's body can be used as a rudder, allowing the current to force it across the river bottom in alternating directions. When initiating the search, the diver has slack in the line and swims to the right (or left) until the line becomes taut. The diver then turns onto his or her right side, grasps the line with the right hand (both hands are needed in very strong currents), and stiffens his or her body, turning it at an oblique angle so that the current sweeps it rapidly to the left. As the arc slows, a conventional swimming position is assumed and the diver swims upstream and shoreward. When swimming against the current becomes difficult, the diver shifts the line to his or her left hand, turns on his or her left side, and repeats the procedure in reverse mode. As progress is made across the bottom, the diver slips backward along the line, gradually making larger and larger arcs. The size of the arc depends on current velocity and line length. If the object of search is not found, the diver returns up the line to the pivotal point, relocates the anchor, and begins again.

8.2.3 Jackstay Search Pattern

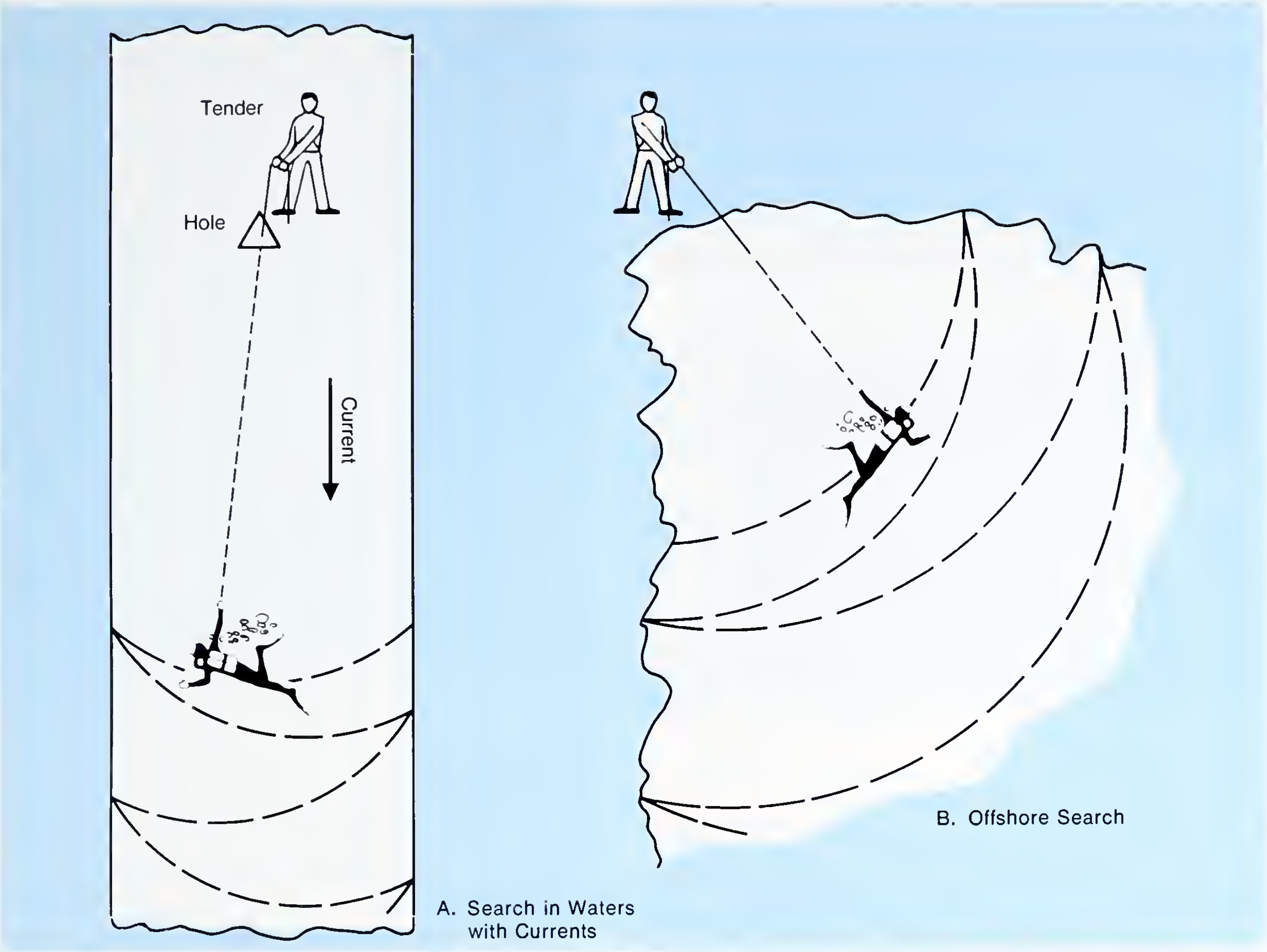
In the **jackstay search pattern**, a rectangular search area is laid out and buoyed (see Figure 8-11A). Buoy lines run from the bottom anchor weights to the surface, and a ground line is stretched along the bottom

Figure 8-9
Circular Search Pattern
Through Ice



Courtesy Clifford Ellis

Figure 8-10
Arc (Fishtail) Search Pattern



A. Search in Waters with Currents

B. Offshore Search

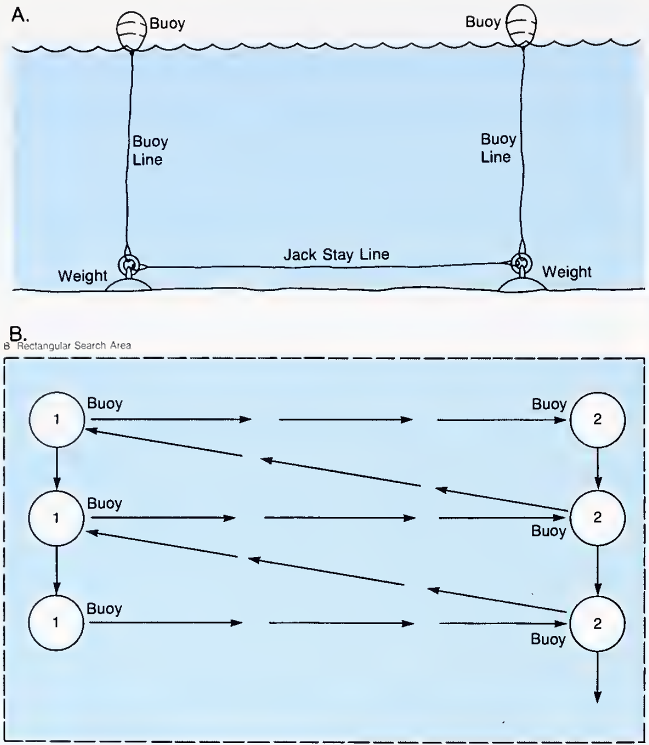
Courtesy Clifford Ellis

between the weights. The divers conducting the search descend on the buoy line and search along the ground line, beginning at one of the anchor weights. When the searching diver reaches the other anchor weight, the weight is moved in the direction of the search. The distance the weight is moved depends on visibility; if visibility is good, the weight is moved the distance the searching diver can comfortably see as he or she swims along the line. If visibility is poor, the line is moved only as far as the searching diver can reach. The searching diver then swims back toward the first anchor weight along the ground line (Figure 8-11B). The length of the ground line determines the area to be covered. The jackstay search pattern is the most effective search technique in waters with poor visibility.

8.2.4 Search Using a Tow Bar

The **tow-bar pattern** is similar to the aquaplane method illustrated in Figure 8-21. It involves the use of a metal bar 4 to 10 feet (1.2-3.0 m) long that permits two divers to be towed behind a boat (liveboating). The area to be searched is marked off with four diving flag buoys, one at each corner, to form a square or rectangle. The distance between the buoys depends on the size of the area to be searched and the maneuverability of the boat. After the buoys are in place, the divers grasp the tow bar and are pulled parallel to two of the buoys at a slow rate of speed. After the divers have passed the last buoy, the boat is brought about through the center of the square and parallel to the buoys. A second pass is made along the buoys, one boat width away. This pattern is continued until the buoyed area has been searched completely. Two of the buoys can then be moved to the far side of the second set of buoys, forming another square. This technique is shown in Figure 8-12. (The procedures and safety precautions associated with liveboating are described in Section 8.10.1.)

Figure 8-11
Jackstay Search Pattern



Source: NOAA Diving Program

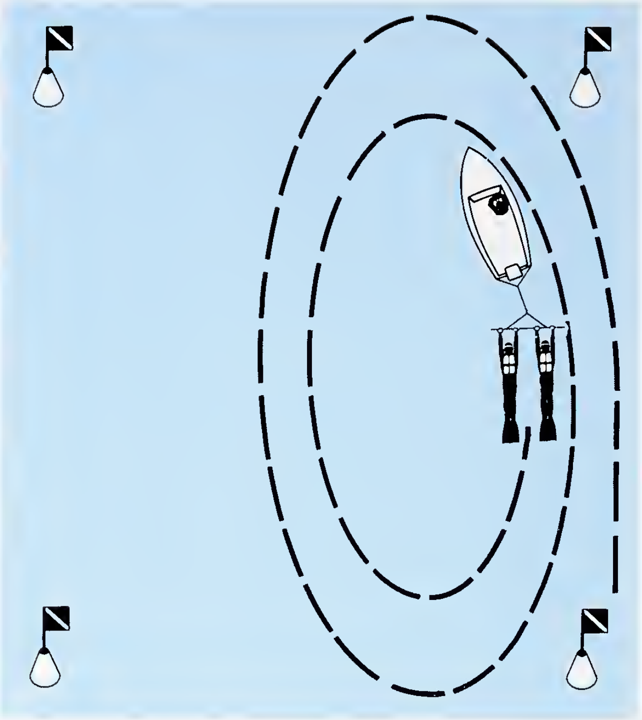
8.2.5 Search Without Lines

When conditions are such that search lines cannot be used, a search can be conducted using an **underwater compass**. There are many search patterns that will ensure maximum coverage; however, simplicity of pattern is important. Divers should use the cardinal points—N, E, S, W—and the length of a side—one-minute intervals or 50 kicks—and should turn the same way each time.

In addition to observing the usual safe diving practices, divers conducting searches should consider the following:

- When plastic-coated steel wire is used as a line marker, a small pair of wire cutters should be carried to permit escape from entanglement.
- To prevent line fouling when two tethered divers are used in search patterns, one should be designated as the inside diver; this diver always remains under and inside the position of the other tethered diver.
- When untethered divers are involved, it is advisable to use contrasting materials for radius, boundary, and distance lines to decrease the possibility of a diver becoming lost. Polyethylene line provides a good contrast to plastic-coated stainless steel wire and is recommended for boundary lines.

Figure 8-12
Searching Using a Tow Bar



Courtesy Clifford Ellis

8.2.6 Recovery

The method chosen to recover a lost object depends on its size and weight. Small items can be carried directly to the surface by the diver, while larger items require lifting devices (see Section 8.9.1). When a lift is used, the diver must attach lifting straps and equipment to the item being recovered. A line that is longer than the depth of the water being searched and that has a small buoy attached should be carried to the spot to mark the located object.

8.3 UNDERWATER NAVIGATION

At present, all readily available diver navigation or positioning systems rely on surface position for their origin. If navigational or geodetic positions under water were used, the origin would have to be extrapolated, which would introduce an additional margin of error.

Recently, **acoustic telemetry** techniques, which use microprocessor-controlled methods, have been applied to diver navigation. These systems can be used to track divers from the surface and to guide them to particular locations. Newer methods will allow divers to take the system along to monitor their own position (Woodward 1982); however, **dead reckoning** is still the most common form of underwater navigation. This procedure has a long history and is used because it is impractical for divers to carry and operate cumbersome and complex navigation equipment. An acoustic-based navigational system has recently been developed that uses a person's sensory ability to differentiate the time-of-arrival of underwater sounds at the two ears. If a sequence of sounds is produced along a line, a person interprets them as deriving from a moving sound source, just as a person perceives the lights being sequentially turned on and off on a theater marquee as moving. A diver can quite accurately perceive the center of a sound array and swim to it from distances as great as 1000 feet (303 m). This technique can be used in habitat operations and when diving in murky water.

Sonar is another method of increasing a diver's ability to navigate under water. Divers may find carrying a compact active sonar useful for avoiding obstacles. Underwater diver-held sonars have been used with some success for years (Figure 8-13). The effectiveness of sonar operations is related directly to the level of a diver's training; many hours of listening to audio tones in a headset are required before a diver can "read" the tones. When using diver-held sonar, the diver makes a slow 360-degree rotation until the object is located and then notes the compass heading. The active range of most diver-held sonars is about 600 feet (182 m). In the passive or listening mode, pingers or beacons sometimes can be detected as far away as 3000 feet (909 m). For shorter ranges, there are units that allow a diver to point the device ahead and obtain a direct readout in feet for distances up to 99 feet (30 m) with a reported accuracy of 6 inches (15.2 cm) (Hall 1982).

Acoustic pingers are battery-operated devices that, when activated, emit a high-frequency signal. Pingers are the companion units to pinger locators; locators are used in the passive mode. Pingers can be attached to any underwater structure, including:

- Habitats;
- Submersibles;
- Pipelines;
- Wellheads;
- Hydrophone arrays;
- Wrecks; and
- Scientific instruments.

Divers have had some success in locating underwater structures with acoustic beacons that emit signals within the audible frequency range. In some cases, single beacons have been as accurate as dead reckoning; however, the sequentially activated acoustic array system has been shown to be superior to either pingers or dead reckoning.

Figure 8-13
Diver-Held Sonar

Courtesy Dukane Corporation

For relatively short underwater excursions, however, the **compass, watch,** and **depth gauge** are still the simplest navigational devices available. Once a compass bearing has been ascertained, the diver swims along the line of bearing, holding the compass in a horizontal position in front of him or her. Progress is timed with the watch, and the depth is noted. To swim a good compass course, the axis of the compass must be parallel to the direction of travel. A simple and reliable method of achieving this is for divers to extend the arm that does not have the compass on it in front of them and then to grasp this arm with the other hand (i.e., the arm to which the compass is strapped) (Figure 8-14). Swimming with the arms in this position helps divers to follow the desired course and, in low visibility, prevents them from colliding with objects. Practicing on land by walking off compass courses and returning to the starting point helps to train divers for underwater navigation. Because the accuracy of a compass is affected by the presence of steel tanks, it is advisable to determine a compass's deviation in a pool with a second diver swimming alongside and varying the course. A depth gauge or watch should not be worn on the same arm as the compass because it may cause a deviation in compass heading.

A diver can calculate his or her transit time by using the following formula to estimate distance:

$$T = \frac{D}{S}$$

where

T = transit time in minutes
D = distance to be covered in feet
S = speed of advance in feet per minute.

A diver can estimate speed by swimming at a pace easily maintained over a known distance and slightly modifying the formula to:

$$S = \frac{D}{T}$$

For example, a diver traversing a 1000-foot (305 m) course in 10 minutes is swimming at a speed of 100 feet (30.5 m) per minute, or approximately 1 nautical mile (1.85 km) per hour.

Some underwater topographical navigation aids that can be used are underwater landmarks (and turns made with respect to them), the direction of wave ripples in the sand, and the direction of the current (if it is known that the current will not change during the dive). Some areas require the use of a transect line because they lack distinct bottom features. Divers often use the increase in pressure against their ears and masks or changes in the sound of exhaust bubbles to identify changes in depth.

8.4 UNDERWATER TOOLS

A fundamental aspect of accomplishing work under water is the selection of proper tools and equipment. In all operations, the relative advantages and disadvantages of power tools and hand tools must be considered. The amount of effort that will have to be expended is an important consideration in underwater work, and power tools can reduce the amount of physical exertion needed. Having to supply tools with power and to transport them, however, may be a substantial disadvantage.

The performance of divers under water is degraded by several factors, including water resistance, diver buoyancy, equipment bulk, the confined space environment, time limitations, visibility restrictions, and a diver's inability to provide a proper amount of reaction force without adequate staging, hand grips, or body harnesses. A diver's performance may therefore decrease significantly compared with his or her performance on land. Even a relatively simple task like driving a nail can be difficult because of limited visibility, water viscosity, and other environmental factors; however, some tasks are easier to accomplish under water because of the diver's ability to move easily in three dimensions. Because diver safety is a primary consideration in any underwater operation, hazards such as electric shock, excessive noise, and other potential causes of injury must be taken into account when selecting underwater tools.

Table 8-2 lists some common tools used under water, along with their sources of power and available accessories. Most pneumatic and hydraulic tools can be adapted for underwater use. The information supplied by the tool's manufacturer contains detailed use specifications that should be observed faithfully.

Figure 8-14
Using a Compass for Navigation

Photo by Bonnie J. Cardone

8.4.1 Hand Tools

Almost all standard hand tools can be used under water. Screwdrivers are generally available in three configurations: the machine (or straight-slotted) type, the phillips type, and the allen type. Of the three, the allen screwdriver is easiest for a diver to use, because only torque is required to operate it and the linear reaction force necessary is minimum. Also, the allen type provides a longer lever arm. The other types of screwdriver have a tendency to slip out of the screw head or to damage the screw by twisting. A single multipurpose tool can be made by welding a screwdriver blade and a pair of pliers to an adjustable wrench.

When using a hand saw under water, it is difficult to follow a straight line. An added complication is the tendency of the blade to flex, which increases the likelihood that the blade will break. Because it is easier for

Table 8-2
Diver Power Tools

Tool	Type	Description/Function/Accessories
Drill	Hydraulic	Metal and wood bits to 3"; attachments for brushing, grinding, cutting, and tapping
	Pneumatic	Metal and wood bits, star drills, and other accessories for heavy-duty work
	Electric	5/8 hp motor; used for drilling, tapping, grinding, and brushing
Impact wrench	Hydraulic	3/4" to 2 1/2" square or hex drives; 100 to 10,000 ft-lb on bolts to 3"; also used to drill and tap; larger tools weigh 12-80 lbs
	Pneumatic	1/4" to 4" square drives; handles bolts to 12"; largest tool weighs 600 lbs
	Electric	250 ft-lb on 3/4" bolts; 1/2" hex drives; 800 and 1200 rpm
Cable cutter	Hydraulic	Pressures to 10,000 psi over ambient; guillotine-type cuts cable to 2 1/2"
	Power velocity	Guillotine-type cuts cable to 1 1/2"
Stud driver	Power velocity	Penetrates plate from 1/4" to 1 1/4" thick
Abrasive saw	Hydraulic	4" cut; 6" to 10" wheels
	Pneumatic	4 1/2" cut
Grinder	Hydraulic	Hydraulic 9" wheel (7" max. recommended)
	Pneumatic	8" wheel
Chain saw	Hydraulic	To 15 hp; bar length to 43"; used for wood only
Hole cutter	Hydraulic, Pneumatic, Electric	To 4" diameter
	Explosive	Shaped charge, cuts 4" hole in steel up to 2" thick
Milling cutter	Hydraulic	Cuts large holes up to 72" in diameter in bulkheads
Hacksaw	Hydraulic Pneumatic	8 1/2" cut for wood; models also available for metal and pipe; 14" cut for wood; shorter for metal, pipe
Hammer	Hydraulic	Used for hammering, chipping, punching, and chiseling; develops 40 ft-lb; delivers 1 to 300 blows per minute
	Pneumatic	Standard paving breaker
Jackhammer	Pneumatic	Turns and reciprocates
Spreader (Hurst Tool)	Hydraulic	Jaws open/close with 6 tons' force, 32" spread
Band saw	Hydraulic	Used for cutting soft metals and cables

Sources: Hackman and Caudy (1981)
NAVSEA (1982)
Penzias and Goodman (1973)

a diver to pull than push under water, it is useful to put the blade in the saw so that the sawteeth are oriented toward the diver and the cut is made on the draw.

A 2- to 4-lb short-handled hammer is a commonly used underwater tool. Because considerably more effort is required to swing a hammer under water than on land, it is easier to develop force by pounding with the heavy weight of a sledge hammer than by swinging and hitting with a lighter hammer.

Because it is easy to lose or drop tools under water, they usually are carried to the work site in a canvas bag and are then attached to the diver's belt with a line. They also can be attached to a descending line with a shackle and be slid down this line to the job site from the surface. Tasks involving grinding, chipping, pounding, or reaming with hand equipment are arduous and time consuming, and the use of hand tools for these tasks is not practical unless the task is small. To protect hand tools after use, they should be rinsed with fresh water and lubricated with a protective water-displacing lubricant.

8.4.2 Pneumatic Tools

Although pneumatic tools are rarely designed specifically for use under water, they need little, if any, alteration to be used in this medium. According to Hackman and Caudy (1981), the power available in air motors ranges from 1/8 to 25 hp, and loaded speeds range from 40 to 6000 rpm; some of these tools have even higher speeds. Most pneumatic tools require 90 psig of air pressure to operate, and they exhaust into the water. A disadvantage of these tools is that they exhaust bubbles that may disturb divers or impair their visibility under water. In addition, the amount of pressure available for power decreases at depth. Pneumatic tools can be modified to include a hose attachment on the exhaust that is larger in diameter than the supply hose. Often, the exhaust hose is routed back to the surface, where it discharges to atmospheric pressure. Even with these modifications, surface-supplied pneumatic power can be used only to depths of 100 to 150 feet (30.5-45.7 m). Although closed-circuit pneumatic tools would not be as wasteful of energy at depth as open-circuit tools, they have not been developed because the entire system would have to be pressurized or the tool would have to be designed to withstand ambient water pressure. The extensive maintenance requirements of pneumatic tools can be minimized by using in-line oilers to meter oil automatically into the air supply hose. After each day's diving, oil should be poured into the air inlet of the tool until it completely fills the motor section; the tool should then be submerged in an oil bath before being turned on once to displace any water trapped in the tool.

8.4.3 Hydraulic Tools

Hydraulic tools are the most popular kind of tool with working divers because they provide consistent closed-cycle power, are safer to use under water, have little or no depth limitation, are much lighter per unit of power output, do not produce bubbles that obscure the diver's vision, and require relatively little maintenance. As with pneumatic motors, hydraulic systems have the capability to start and stop rapidly, and they can be operated at different speeds.

Tools such as drills (Figure 8-15A), impact wrenches (Figure 8-15B), chain saws, disc grinders (Figure 8-15C), and cable or pipe cutters usually are modified versions of hydraulic tools designed for use on land. To convert tools for underwater use, different seals are used, internal voids are compensated to withstand ambient pressure, external surfaces are painted or coated with a corrosion inhibitor, and dissimilar metals are insulated from each other.

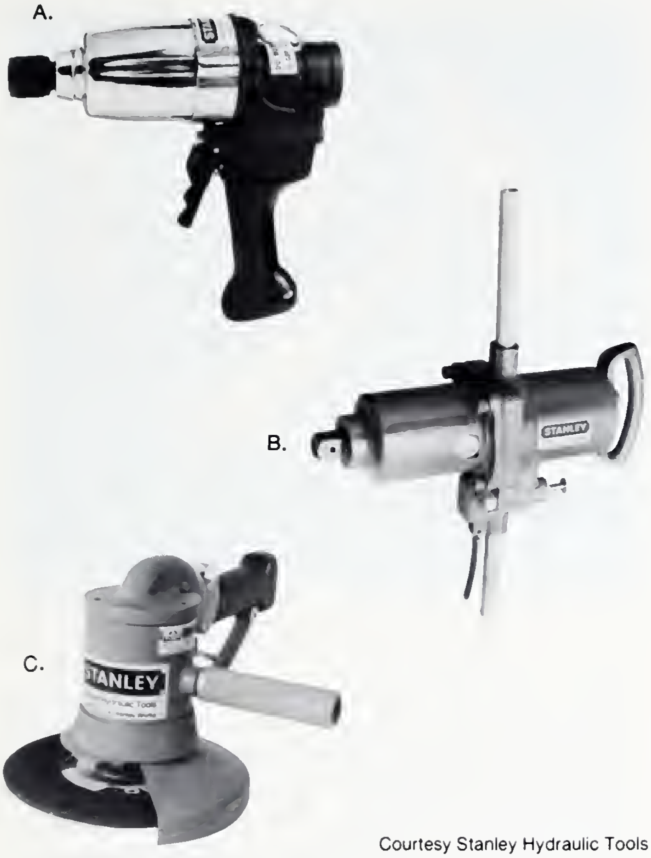
To facilitate the field use of hydraulic tools in areas where hydraulic oil is not readily available or where environmental restrictions prohibit the discharge of oil, hydraulic tool systems are being developed that use seawater as the working fluid in place of oil. The Navy has supported a program, called the "Multi Function Tool System," that involves the development of a seawater hydraulic grinder, band saw, impact wrench, and rock drill specifically for underwater use.

Hydraulic tools require a power source at the surface or a submersible electrohydraulic power source that can be located at the work site near the diver. These power sources are compensated to operate at all depths but require built-in batteries or an electrical umbilical from the surface to run the motor. The tools normally operate at pressures from 1000 psi to 3000 psi. To use them, divers usually work standing on the bottom or on some structure. When working with these tools on the side of a structure or in the midwater column, a diver can use harnesses or a diver's stage for support.

The U.S. Navy has adapted and developed a variety of diver-operated hydraulic tools for construction and salvage work. These tools include:

1. An abrasive saw (2000 psi, 6-14 gpm, 10-in. dia. by 1/8-in. thick blade);
2. A grinder (2000 psi, 11 gpm, used with discs, cups, or wire brush);

Figure 8-15
Underwater Hydraulic Tools



Courtesy Stanley Hydraulic Tools

3. A come-along (1500 psi, 2000 lb. force, moves cable 1.5 in. per stroke, used as a rigging aid);
4. A hurst tool (input of 5000 psi and .07 gpm, jaws of tool open and close with force of 6 tons through a distance of 32 inches);
5. Impact wrenches (2000 psi, 5 gpm, used for drilling, tapping, or for make/break of nuts and bolts);
6. Linear actuators (10,000 psi rams, 8 ton pull-cylinders, 10,000 psi cutters or 2 1/2 in. wire rope, rebars, or splitting nuts);
7. A pump (2000 psi, 5 gpm hydraulic fluid; 100 psi, 400 gpm water flow, used for jetting, washing, and dredging); and
8. Hose reels and different hydraulic power supplies.

(An excellent source of information on the operation and maintenance of the Navy's hydraulic tool systems is NAVSEA 1982.)

Some hydraulic tools have been designed solely for underwater use. There is, for example, a hydraulic hammer that operates on 2000 psi, 0.5 to 3.0 gpm, and develops a 40-foot-pound force per blow; output speed ranges from 1 to 300 blows per minute. The unique design uses compressibility of the hydraulic fluid to generate and store the impact energy.

Hydraulic tools that minimize diver fatigue and discomfort should be selected. Most tools can be reconfigured or redesigned to increase diver comfort. More attention should be given to underwater human engineering principles in the design of new tools. Areas where progress could be made include weight reduction, special grips and triggers, placement of handles at the center of gravity or wherever they will best counteract torque, and reduction of vibration and reaction forces.

Hydraulic tools are easy to maintain. They should be rinsed thoroughly with fresh water after each use and then be sprayed with a protective lubricant such as WD-40.

8.4.4 Electric Tools

Underwater tools that operate by electric power have been designed, developed, and manufactured, but they are seldom used. The AC motor, stator, and control electronics of such tools are potted in epoxy, and the motor is water cooled and water lubricated. Electric tools require only a small umbilical, have no depth limitation, and are reasonably light in weight. Although ground-fault detector circuitry is provided, the fear of electric shock persists, and most divers consequently prefer to use hydraulic tools despite their greater weight and support equipment requirements.

8.4.5 Power Velocity Tools

Power velocity tools are actuated by the firing of an explosive cartridge, which increases the pressure behind a piston to accelerate a stud or a cutter into the work piece (Figure 8-16). Power velocity tools are used to attach padeyes, studs, and hollow penetrations in plate steel. Different configurations are used to cut cable, rebar, hydraulic/electrical umbilicals, and to drive an impact socket for loosening jammed nuts. Studs are available to penetrate steel that is at least 1/4-inch thick (0.64 cm). The cutters can sever 1.5-inch (3.8 cm) in diameter cables or 2-inch (5.1 cm) in diameter composite umbilicals.

WARNING

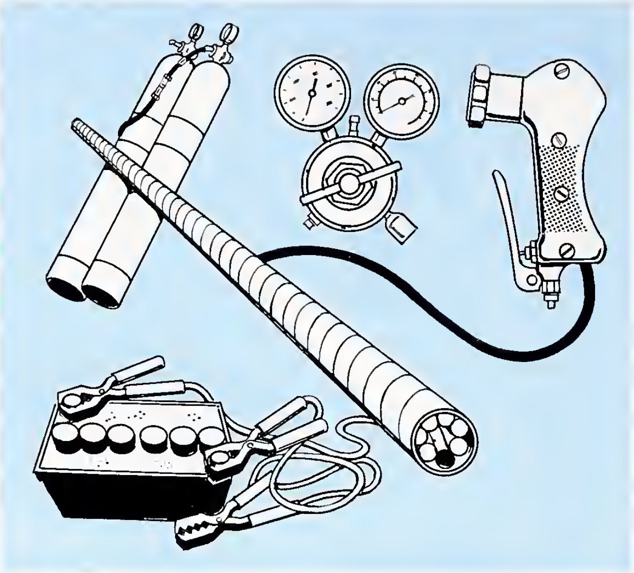
Only Properly Trained Personnel May Handle Explosive Cartridges. Trained Divers Also Should Use These Tools Only When The Proper Safety Precautions Have Been Taken

Power velocity tools are well suited to most underwater work. Their weight is comparable to that of

Figure 8-16
Explosive Hole Punch

Courtesy Battelle-Columbus Laboratories

Figure 8-17
Oxy-Arc Torch



Courtesy Broco, Inc.

hydraulic tools, but they require no umbilical or power line. Some models of underwater stud guns feature barrels that can be replaced easily by the diver. The heavier duty models, as well as most cutters, require that reloading be performed on the surface.

8.4.6 Cutting and Welding Tools

Cutting and welding are often required both in seawater and in dry underwater enclosures or habitats. Since habitat welding involves techniques and tools similar to those of atmospheric welding, this manual addresses only cutting and welding tools that are used in seawater. Underwater cutting and welding processes emit toxic gases that rise to the surface and, since they are heavier than air, collect in any low-lying confined areas. Ventilation during underwater cutting and welding is thus essential to protect both divers and surface personnel.

The most popular cutting torch is oxy-arc (Figure 8-17); the process is learned with less training than oxy-hydrogen, oxy-acetylene, or shielded metal arc cutting. The oxy-arc process uses electric power to heat the work piece to ignition temperature; a jet of oxygen is then directed at the heated spot and the metal burns or oxidizes very rapidly. Electric current is not required for oxy-hydrogen, but an air hose is required to fill a shield cup around the tip to stabilize the flame and to hold water away from the area of metal being heated. The metal is heated to ignition temperature by a hydrogen/oxygen flame, and pure oxygen is then directed at the heated spot to start the cutting action. Although acetylene also has been used as a fuel gas for cutting, it is considered unsafe to use at depths greater than 30 feet (9.1 m). Shielded metal-arc cutting is a process in which metal is severed simply by melting and physically pushing the metal out of the kerf. An electric arc is formed between the electrode and the work piece to provide the heat for melting. The process is used in situations where no oxygen is available. Some believe that shielded metal-arc cutting is superior to oxygen cutting on steel plates less than 1/4 inch (0.64 cm) thick or when cutting brass, copper, or copper-based alloys. Oxy-arc is used to cut steel up to 2 inches (5.1 cm) thick.

The most widely used underwater welding process is shielded metal-arc welding. The weld is produced by heating with an electric arc between a flux-covered metal electrode and the work piece. The heat developed by the arc causes the base metal parts, the core wire of the stinger, and some of the flux covering to melt. Other constituents of the flux decompose to gases, which shield the molten metals somewhat from contamination. When welding under water, technique is important and special training is required. Generally, underwater welds are not as strong as surface welds because of water quench and contamination. Also, it is vitally important that the diver be aware at all times of the severe shock hazards associated with electric cutting and welding processes. Metal helmets must be insulated.

WARNING

Diver Training and Experience Are Essential in Underwater Cutting or Welding

8.5 MAINTENANCE AND REPAIR TASKS

Maintaining and repairing equipment, structures, and instruments under water requires skill and an understanding of the work to be done. In addition, underwater maintenance should be performed only when environmental conditions are acceptable.

If practical, divers should practice underwater tasks in shallow water before attempting them in deep water. The time that will be needed to accomplish the task must be known to enable the diver to complete the task (or a major portion of it) within the constraints of the air supply. For strenuous tasks, the work should be divided into subtasks and several divers should take turns carrying them out.

To accomplish underwater work, four task phases are involved:

- Inspection of the work site and determination of the condition of the equipment that needs maintenance or repair;
- Selection of appropriate tools;
- Performance of the repair or maintenance task; and
- Reinspection to ensure that the work has been accomplished successfully.

Most underwater maintenance and repair tasks that a diver is asked to perform are associated with the inspection and repair of a ship's rudder, propeller, sea chest, or cathodic protection system. When a diver is working over the side of a ship to perform a maintenance task, the ship's propeller should be locked out and the rudder should be held in static position. The appropriate international code flag should be hoisted.

Divers should be careful to avoid skin contact with the hull of the ship on which they are working, because toxic paints are often used on the hull to inhibit marine growth (barnacles, algae). These paints retain their toxic qualities for months after the freshly painted ship has been returned to the water.

Maintenance and repair tasks can be accomplished more easily if a restraining system is used. Such a system can be as simple as a line for the diver to hold onto that is attached to a convenient point or as elaborate as a jacket with magnets or suction cups that attach to a shear plate.

8.6 INSTRUMENT IMPLANTATION

The proper implantation of scientific instruments is important to the success of underwater scientific investigations. Instruments that are implanted on the sea bottom include lights, cameras, positioning stakes, radiometers, recording current meters, thermistors, oxygen sensors, and acoustical devices. Factors affecting the success of implantation are:

- The instrument's size and weight, mounting dimensions, fragility, and attachment points
- The available power supply and instrument readout cables, or (if self-contained) the frequency with which the instrument's batteries must be changed or the instrument must be serviced or replaced
- The alignment of the instrument in position, its height above the bottom, and its sensitivity to misalignment
- Bottom conditions, the bearing strength of the bottom, anticipated currents, and the type of marine life
- The precise markings of instrument location and the methods used for recovery at completion of the mission.

The size and weight of the instrument and its physical dimensions and fragility affect the type of anchor used and the techniques chosen to move the instrument to the site. For small instruments, a concrete block may be an appropriate anchor. The blocks can be predrilled, fitted with fasteners on the surface, and moved to the site as a unit and positioned. In other cases, the concrete block and instrument can be moved to the site separately, and a diver can then position and align the instrument in the water. A concrete block anchor can be lowered directly into position using a winch, or it may be fitted with flotation devices and guided into position by a diver, who removes the flotation device when the anchor is in position.

For large instrument packages, anchors can be made of metal piles that are driven into the bottom by a diver using a sledgehammer or pneumatic impact hammer. Steel pilings create magnetic anomalies that can affect instrument readings; instruments should therefore be used only after the effect of the pilings on the instrument's functioning has been calibrated. Pilings may be grouted in place with concrete supplied from the surface. Embedment anchors can be used to stabilize an instrument installation and can be driven into the bottom to secure the lines. Chains or wires equipped with turnbuckles can be run over the instrument package between anchors to secure the installation further. The foundation package should be designed to accept the instrument package easily so that it is as easy as possible for the diver to attach the package. When the foundation is complete, a line or lines should be run to the surface to assist in lowering and guiding the instrument into place.

Many underwater instruments require outside power to operate and to transmit data to outside receivers. During the installation of instrument cables, a diver usually is required to anchor the cable at various points along the cable run. The first point of anchor should be near the instrument package. To reduce the possibility that the cable will topple the instrument or that movement of either the cable or instrument will break the cable connection, the diver should allow a loop (called a bight) of extra cable between the first anchor and the instrument. The diver should guide the instrument cable around any rocks or bottom debris that might abrade the cable covering. Anchors should be placed at frequent intervals along the length of the cable, wherever the cable turns, and on each side of the cable where it runs over an outcropping or rise in the bottom. Cable anchors can either be simple weights attached to the cable or special embedment anchors.

The alignment of the foundation is important to successful implantation. A simple technique to achieve alignment is to drive a nonferrous stake into the bottom that has a nonferrous wire or line attached and then to hang a compass from the line or wire. A second nonferrous stake is then driven into the bottom when the compass indicates that the alignment is correct. The two stakes and the attached line then act as the reference point for aligning the foundation or instrument. A tape is used to translate measurements from the reference stakes and line to the foundation or the instrument.

Before selecting a location for an instrument, bottom conditions should be analyzed to identify the appropriate foundation. The instrument site should be reinspected at frequent intervals to monitor the condition of the instrument and to clear away sediment or marine growth that may affect instrument readings.

Unmanned instrumentation is increasingly used for long-term data-gathering and environmental monitoring tasks. Because many unmanned instruments are self-contained and expensive, they must be equipped with reliable relocation devices. Although surface or subsurface buoys (used in combination with LORAN-C or satellite navigation systems) are the most common relocation devices, at least for short-term implantation, these buoys are subject to vandalism, fouling in ship propellors, and accidental release. Many users therefore equip these instruments with automatic pinger devices in addition to marker buoys (see Section 8.3).

If a pinger-equipped instrument is believed to be lost in the vicinity of implantation, a surface receiver unit operated from a boat can guide divers to the approximate location; they can then descend and search with a hand-held locator unit. This technique works especially well in murky water when the divers are surface supplied and use liveboating techniques (see Section 8.10.1), particularly if the pinger is weak and a long search is necessary.

8.7 HYDROGRAPHIC SUPPORT

In hydrographic operations, divers can be used to confirm the existence and/or location of hazards to navigation, locate and measure least depths, and resolve any sounding discrepancies identified by different surface-based measurement techniques. When using divers for this type of work, it is essential to consider the skills of the divers, water conditions, the nature of the work, special equipment requirements, and the availability of diver support. Because hydrographic operations are frequently conducted in open water, it is important to mark the dive site using buoys, electronic pingers, or fathometers; this precaution becomes increasingly important under conditions of reduced visibility and high currents.

8.7.1 Hazards to Navigation

A significant portion of hydrographic support diving is conducted to identify hazards to navigation. Once the general location of a navigational hazard has been identified, its precise location can be determined using the search techniques described in Section 8.2.

When the object has been found, it should be marked with a taut-line buoy and its geographic position should be noted. If the depth is shallower than about 50 feet (15.2 m), a lead line depth should be recorded, along with the time of notation.

Diving operations that are designed to prove that no navigational hazard exists in a particular area are extremely time consuming and require painstaking documentation of search procedures and location. The reported location and geographic position of the hazard should be marked precisely; a taut-line buoy should be used to mark the search control point. Any time the control point is moved, the move should be documented and the geographic position of the new control point should be noted. Documentation of the search should include the geographic position of control points, the type of search, the equipment used, water conditions, and problems encountered, what was found or not found, and a statement describing the area that has been searched and any area that may have been missed.

8.7.2 Locating and Measuring Least Depths

Divers can be used to determine least depths accurately, especially in such areas as rocky shoals, coral reefs, and wreck sites. After the general location to be studied has been identified, a diver is sent down to mark precisely the least depth by tying off a line on the bottom so that a buoy floats directly overhead. Care must be taken to ensure that the lead line is plumb and that the time of marking is recorded. A taut-line buoy can be used to mark the geographic position of the least depth so that it can be noted and recorded by surface personnel.

8.7.3 Resolving Sounding Discrepancies

When measurements of undersea features are discrepant, divers can be used to inspect the site, resolve the discrepancies, and mark the site correctly. Discrepant measurements are most likely to occur in areas such as rocky substrates, faulted or volcanic bottoms, and reefs.

8.8 WIRE DRAGGING

Wire dragging is a method of ensuring that surface ships can pass through an area safely. The method involves deploying a wire between two ships and holding it at depth with weights ranging from 50 to 250 pounds (22.7-113.4 kg). The objective of this procedure is to tow the wire in such a manner that hydrodynamic forces induce an arc-shaped curve. As the ships move through the water, the wire will snag on obstructions protruding above the depth of the drag. Divers supporting wire-dragging operations are used to identify:

- The objects on which the wire hangs;
- The least depth over the obstruction; and
- The highest protrusion that could be caught from any direction.

Divers also can identify underwater features that pose a hazard to fishing nets and trawling or ground tackle and assist in the removal of minor obstructions. Another task performed by divers is assessing the areal extent of wreckage. If the least depth cannot be determined accurately, the approximate depth needed for clearance is sought.

Divers need to exercise extreme caution when working around wire drag hangs because, in addition to the hazards associated with any wreck diving operation, the wire itself poses a hazard. For example, if the wire slips on an obstruction, it could pin a diver; if the strands of the wire are broken, the wire can cut a diver severely; and if a diver holds the wire and it pulls loose, it can sever the diver's fingers.

When an underwater obstruction needs to be investigated, the support boat must be tied off to the buoy nearest the obstruction. After agreeing on all procedures, the divers swim to the buoy and descend to the bottom wire. Depth gauges are checked, and the depth of the obstruction is noted on a slate.

Because of forces acting on both the wire and the upright to the buoy, the depth at the weight can vary from its setting by as much as 10 feet (3 m). Once on the bottom, the divers proceed hand-over-hand along the wire, one behind the other, taking care to stay outside the bight of the wire. This may be difficult because most drags are run with the current, which tends to push the diver into the bight. The recommended procedure is to "crab" into the current, making every effort to stay as much above the wire as possible.

WARNING

Divers Must Be Extremely Careful When Working Inside the Bight of a Ground Wire

After arriving at the obstruction, wire depth is recorded. The divers then try to find the least depth of the obstruction; this procedure requires the divers to leave the wire. If the obstruction is not substantial, the divers should be several feet above the obstruction's depth when they enter the bight. Once the least depth point is found, the divers record the depth and determine whether the high point could cause the ship to hang at any point. If the object is intact or is a candidate for recovery, the divers select a suitable place to tie off a small buoy. The buoy must be tied off inside the bight so as not to be torn away when the drag wire is recovered.

The depth information recorded is verified by a surface-tended pneumatic pressure gauge. Because the equipment involved is cumbersome, this technique is rarely used during the initial investigation. In relatively calm seas and slack current, a lead line may be used to verify depth information.

Because divers following a wire do so in single file, it is easy for one diver to lose track of his or her buddy. A buddy-check should therefore be carried out every 50 feet (15.2 m); this procedure also may prevent diver entanglement when there is poor visibility.

NOTE
Wire-drag support diving should be done only by experienced divers who are well trained in the techniques and fully aware of the hazards involved.

8.9 SALVAGE

Salvage of a ship or craft, its cargo, or its equipment requires a knowledge both of the technical aspects of recovery and the legal aspects of ownership of the salved items and claims for salvage. A salvor who recovers a ship or craft or its cargo without prior agreement with the owner must file a claim in the United States District Court nearest to the port in which the salved items are landed.

Salvage techniques vary considerably with the size, value, and condition of the item to be salved, the depth of the object and seafloor conditions, and the equipment available to conduct the salvage. Salvage techniques that are used commonly are direct lifts using a winch or crane, floating lifts using a device to compensate for the negative buoyancy of the ship or craft, and repairing and restoring the inherent buoyancy of the salved object itself.

Individual divers often salvage instruments or instrument arrays, anchors, or other small structures. In the majority of these cases, the diver simply carries the item to the surface. In other situations, the diver attaches a flotation device (Figure 8-18) or, for heavy items, a line or wire that will facilitate a direct lift to the surface.

In some salvage operations such as archeological excavations, it may be necessary to clear bottom sediment from around the item before it can be recovered. This procedure is necessary to ensure that the item is free of entanglement. A water jet or air lift commonly is used to clear away entangling debris (see Section 9.12.2).

When working with heavy or overhead items with cables, lines, or chains under tension, divers must develop a sixth sense for safety. Divers should avoid positioning themselves or their umbilicals under heavy objects that might fall or placing themselves above lines that are under tension. The buoyancy or the weight of water displaced from a container by the compressed air necessary to raise an object is equal to the weight of the object in water plus the weight of the container. It is important to remember that:

- The container should be vented to prevent excess air from rupturing it;
- The air will expand if the object is raised from the bottom before all the water has been displaced from the container; this will displace more water and may increase the speed of ascent to an uncontrollable rate;
- The weight of the object in water is reduced by an amount equal to the weight of the water it displaces.

Figure 8-18
Salvaging an Anchor
With Lift Bags

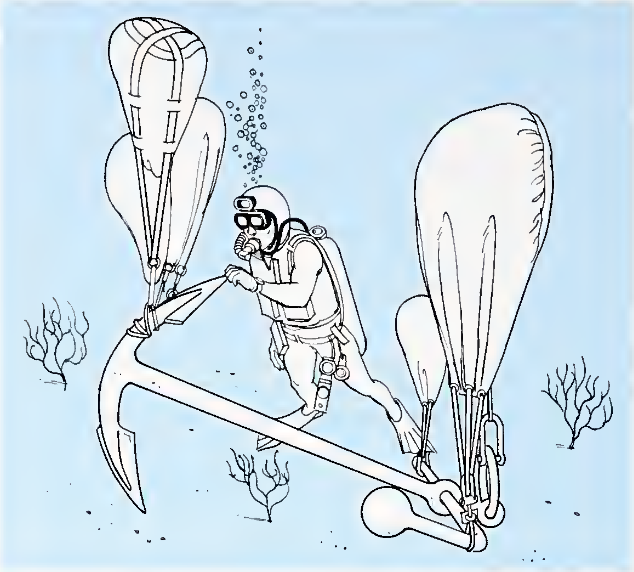


Photo by Geri Murphy

8.9.1 Lifting Devices

Many objects can be used as lifting devices, including a trash can or bucket inverted and tied to the object, a plastic bag placed in a net bag, a 55-gallon oil drum, or a commercially available lift bag (shown in Figure 8-18). If the object is lying on a soft bottom, it may be necessary to break the suction effect of the mud by using high-pressure hoses or by rocking the object back and forth; a force equal to 10 times the weight of the object may be necessary to break it free.

Raising and lowering can be accomplished with commercially available lift bags of various sizes and lifting capacities or with ordinary automobile tire inner tubes. One regular-sized inner tube will lift about 100 pounds (45.4 kg). The tube or tubes are rigged with a short loop or rope holding them together and with the valves pointing toward the bottom. (The valve caps and cores must be removed.) A rope loop is attached to the object to be lifted and is then pulled down as close to the object as possible, because inner tubes have a tendency to stretch to about twice their original length before lifting starts. An ordinary shop air nozzle with a spring-loaded trigger is attached to a short length of low-pressure air hose and is then plugged into the low-pressure port of a single-hose regulator first-stage mechanism. This device is attached to a separate air cylinder for transport to the work site. The end of the nozzle is inserted into the tire valve opening and pushed so that air will not escape. The tube fills, and the object rises to the surface. Care must be taken to leave the valve open, because the expanding air on surfacing could burst a closed system. With practice, objects can be raised part-way to the surface and moved under kelp canopies, etc., into clear water, where they can be surfaced and towed. Divers using this technique should try to accompany the object to the surface and should not stay on the bottom or in any way expose themselves to the drop or ascent path of the object. This technique is especially useful to biologists lifting heavy bags of specimens.

Although the innertube method works, commercially available lift bags are preferred. These bags are designed for heavy duty use, come in a variety of sizes ranging from 100 to 20,000 lbs (45.4-9080 kg) in lifting capacity, and have built-in overpressure relief and/or dump valves. They also are lightweight and readily transportable, e.g., a bag capable of lifting 100 lbs (45.4 kg) weighs only 6 lbs (2.7 kg), and a 1/2-ton-capacity bag weighs only 14 lbs (6.4 kg).

When lifting an object, the lift bag should be inflated slowly from a spare scuba cylinder or other air source. Inflation should cease as soon as the object begins to lift off the bottom. Because air expands as it rises, the rate of ascent may increase rapidly, causing the diver to lose control. Loss of control is dangerous, and it also can cause the bag to tip over when it reaches the surface, spilling the air out and sending the object back to the bottom. The bag's dump valve, therefore, should be used carefully to control ascent.

WARNING

Do Not Use Your Buoyancy Compensator as a Lifting Device While Wearing the Compensator

In addition to the type of lift bags shown in Figure 8-18, special computer-controlled lifting systems have been developed for large salvage jobs (Kall 1984). These systems are relatively insensitive to surface weather conditions and permit both ascent and descent velocities to be held constant even for loads as great as 15 tons. Such systems can be used for emplacing and retrieving heavy instrumentation packages as well as for salvage.

If the object cannot be lifted to the surface directly by winching or lift devices, the rise of the tide can be used if a large vessel or pontoon is available. At low tide, lines are connected tautly to the object and the surface platform; as the tide rises, the load rises with it.

Every salvage project must be planned and executed individually. Novice divers should not attempt underwater salvage tasks for which they are not properly trained or equipped.

8.9.2 Air Lifts

An air lift is used to lift mixtures of water, grain, sand, mud, and similar materials from the holds of ships during salvage operations. In some cases of stranding, an air lift may be used to clear away sand and mud from the side of the vessel (Figure 9-39);

An air lift works on the pressure-differential principle. Air is introduced into the lower end of a partially submerged pipe. The combining of air bubbles with the liquid in the pipe forms a mixture that is less dense than the liquid outside the pipe. The lighter density results in less head pressure inside the pipe than outside, which causes the mixture to rise in the pipe. The amount of liquid lifted depends on the size of the air lift, submergence of the pipe, air pressure and volume used, and the discharge head.

An air lift consists of a discharge pipe and a foot piece or air chamber. The size of the discharge pipe ranges from approximately 3 to 14 inches (7.6-35.6 cm) in diameter, depending on the amount of work to be done and the service intended. The air chamber should be located approximately 20 to 30 inches (50.1-76.2 cm) from the end of the pipe. Table 8-3 may be used as a guide in selecting the size of discharge pipe and air line, taking into consideration the air available and the job to be done.

An air lift operates as follows: the discharge pipe is submerged in the mixture to be lifted to a depth of approximately 50 to 70 percent of the total length of the pipe. The air is turned on, and the lifting operation commences almost immediately. Occasionally, considerable experimentation is necessary to determine the amount of air required to operate the lift efficiently. The use of air lifts in archeological excavation is described in Section 9.12.2.

8.10 DIVING FROM AN UNANCHORED PLATFORM

Diving from an unanchored barge, small boat, or vessel can be an efficient method of covering a large

Table 8-3
Selection Guide For Discharge Pipe and Air Line

Diameter of Pipe, inches	Diameter of Compressed Air Line, inches	Gallons per Minute	Cubic Feet of Air
3	.50	50–75	15–40
4	.75	90–150	20–65
6	1.25	210–450	50–200
10	2.00	600–900	150–400

Source: NOAA (1979)

area for search or survey purposes. When a diver is towed from a boat that is under way, the technique is referred to as liveboating. When a boat accompanies the diver but the diver is not attached to the boat and is being propelled by current alone, the technique is called drift diving. There are procedures and safety precautions that apply to both kinds of diving; these are described below.

WARNING

When Liveboating or Drift Diving, the Engines of Both the Small Boat and Large Vessel (if Any) Should Be in Neutral When the Divers Are Close to the Boat or Are Entering or Leaving the Water

8.10.1 Liveboating

Some underwater tasks require great distances to be covered in a minimum amount of time. These tasks include inspecting a pipeline, surveying a habitat site, searching for a lost instrument, observing fish populations over a wide area, or any number of similar operations. Free-swimming divers are inefficient at carrying out such tasks, and quicker methods of search or survey are needed. Devices such as swimmer propulsion units, wet subs, or towed sleds may be used to increase diver efficiency.

Towing a diver behind a small boat is another method of searching a large area. This technique is called diver towing; the divers hold onto a line attached to the boat and vary their depth according to the contour of the bottom, which allows them to make a closeup search of the area over which the boat is traveling.

WARNING

Liveboat Divers Should Be Careful to Monitor and Control Their Depth to Avoid Developing an Embolism

When liveboating is used, the following safety precautions are recommended:

- If possible, the boat should be equipped with a "jet dive" propulsion system, which has no rudder or propeller.
- If the boat is equipped with a propeller, a propeller cage or shroud should be fabricated to protect the divers.
- A communications system should be set up between the diver and the boat, with signals agreed on and practiced prior to diving. A line separate from the tow or descent line may be employed.
- Divers being towed should carry signal devices (whistle, flare, etc.) especially in adverse weather conditions such as fog, in case they become separated from the boat and tow line.
- Unless there is danger of entanglement, the divers should carry a surface float to assist the boat crew in tracking them. The float line also can be used for signaling the divers while they are on the bottom.
- If diving with scuba, two divers should be towed together.
- If diving with surface-supplied equipment, one diver should be towed while the other remains in the boat suited up and ready to dive.
- A ladder or platform should be available for boarding.
- The boat should be equipped with charts, radio, first aid kit and resuscitator, emergency air supply, and all equipment required by the Coast Guard for safe boating operations.
- The boat operator should know the procedure for alerting the Coast Guard in case of an accident.
- All personnel on board should be thoroughly briefed on the dive plan.

One practical and inexpensive method of liveboating involves the use of a single towline with loops, a tow bar, or a fluked anchor for the divers to hold. Divers using such an apparatus should be towed at a comfortable speed that will not dislodge their masks. The height above the bottom at which the divers travel is controlled by the speed of the boat and the ability of the divers to arch their bodies and to plane up or down. A single towline, rather than a bridle, leading back to a yoke with a short line for each diver works best. There should be two crew members in the tow boat, one to operate the vessel and the other to watch for surfacing divers and to keep the towline from fouling in the boat propeller.

The equipment necessary for towing divers is readily available. The boat should have at least a 30-hp engine and should be large enough to accommodate three or more people and the diving equipment. A towline of 1/2 or 5/8 inch (1.3 or 1.6 cm) nylon line about 200 feet (61 m) long used with about 75 pounds (34 kg) of weight permits divers to reach depths of up to 90 fsw (27.4 m). The towing weight should be made of two or three pieces of lead, steel, or concrete. Three 25-pound (11.3 kg) lead balls are ideal because there is less likelihood that a ball will hang up on submerged objects. A return line of 1/2 inch (1.3 cm) nylon 50 feet (15.2 m) long should be tied to the towline at the weights. Polypropylene line should not be used because it is buoyant. The return line will trail behind the towed divers, who hang onto the towline at or near the weights.

Any time one diver leaves the towline, the partner should monitor the departing diver's actions until he or she has again made contact with the return line. If the diver fails to regain the return line, the partner must abandon the towline and both divers must surface together.

Another liveboating method uses the aquaplane (Figure 8-19). The simplest version is a board that, when tilted downward or sideways, provides a dynamic thrust to counter the corresponding pull on the towing cable. The addition of a broom-handle seat and proper balancing of the towing points permit one-handed control of the flight path. With an aquaplane, which can be made in a few hours from off-the-shelf materials, a team of divers can be towed behind a small boat; as with other towing methods, the maximum speed must be such that the diver's mask is not torn off. The dive team may operate either in tandem off the same board, which requires some practice and coordination, or each diver may have a separate board attached to a yoke.

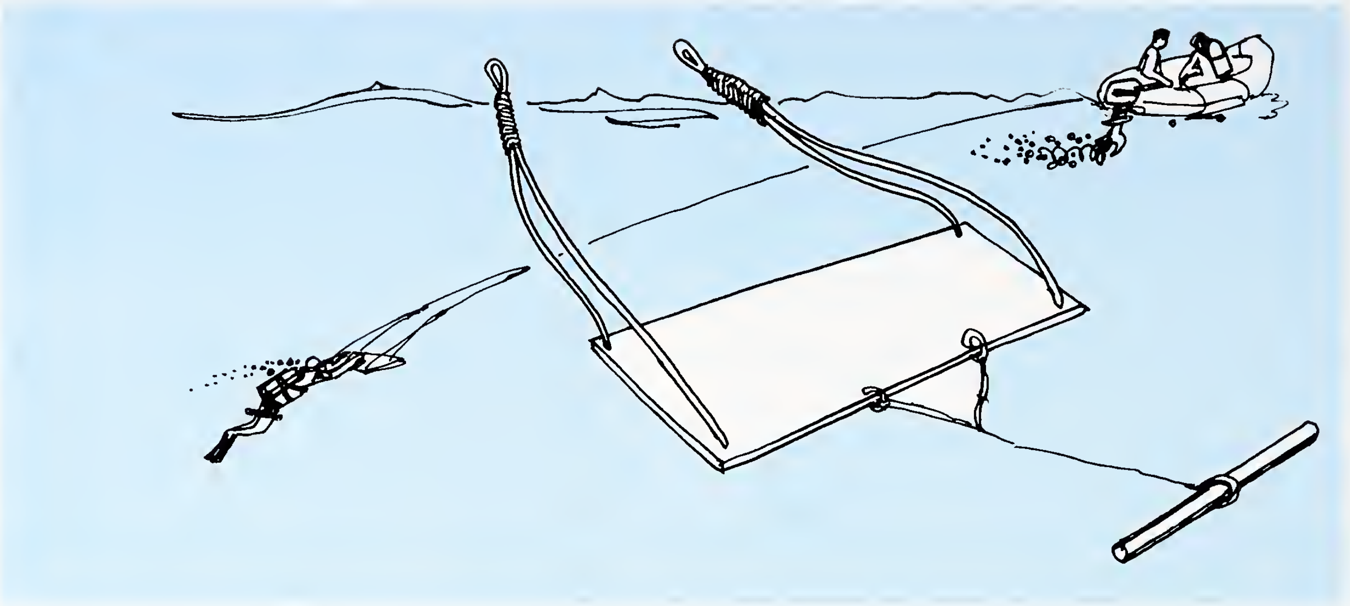
As in the swimming traverse (see Section 10.16.5), the diver keys observation to time. At the same time, a surface attendant notes the location of the tow boat or escort boat as it moves along the traverse, with horizontal sextant angles marking locations versus time. Later, the position of the diver at times of recorded observations can be determined by subtracting the length of the towline from the position of the surface boat at the time of observation.

In areas where entanglement is not a problem, divers may wish occasionally to drop off the towline during traverses to investigate objects of interest. A 50-foot (13.4 m) return line attached to and trailing behind the aquaplane can be used to permit a diver who drops off the sled to grasp the line and return to the sled. It is important for those in the boat to know what the divers are doing, especially if they intend to drop off the line to observe the bottom. A sled or aquaplane released by a diver may continue planing downward by itself and crash into the bottom. Some tow rigs have a small wire built into the towline, with a waterproof pushbutton switch, so that the divers can communicate by buzzer with the tow boat.

One of the best methods of towing divers, especially if they intend to drop off the towline, is to equip each arm of the yoke with a large cork float, such as those used on fishing nets or mooring pickup poles. The diver merely straddles the cork and hangs onto the line ahead. The towing pull is then between the legs and not on the hands and arms. Maneuvering by body flexing is easy, and when the divers wish to leave the line they merely release their grip and spread their legs, allowing the cork to rise rapidly to the surface to let personnel in the boat know the divers are off the line. As soon as the cork breaks the surface, the boat stops, backs up along the line to the cork (the boat must not pull the cork and line to the boat), and hovers, with the engine in neutral, near the bubbles until the divers surface. The divers can then hand over samples, relate findings, and resume the tow. Experience has shown that there is little or no danger of losing the bubbles using this method, because the relatively slow towing speed of the boat allows the cork to surface within seconds of being released. The cork should surface at a point very close to the place where the divers dropped off the line. If this method is not used and if, after the divers drop off a tow, their bubbles cannot be seen from the tow boat, there is a chance that they are temporarily lost. In this case, a standby buoy with an adequate anchor should be ready to be lowered slowly and carefully overboard, so as not to hit the divers below. The towboat should stand by at the buoy until the divers surface. This technique prevents the surface boat from being carried away from the survey area by current or wind.

The scope of the towline may be as much as 10-to-1, and in deep water this could place a diver far behind the tow boat. If a weighted line is used, as described earlier, the scope can be reduced to about 4-to-1. If the diver is a long distance behind the tow boat, a

Figure 8-19
Aquaplane for Towing Divers



Source: NOAA (1979)

safety boat may be used to follow the towed divers to assist them if they become separated from the towline. Whenever a towing operation is planned, regardless of the equipment or method used, it is advisable to conduct a series of practice runs to determine the best combinations of boat speed, towline-yoke length, and diver-boat signals.

Although towing is a useful way to cover a great deal of terrain, there are limitations and drawbacks to this technique. It is difficult to take notes or photographs while under tow, unless enclosed sleds are used. There may be considerable drag on the body, so one should not carry bulky equipment either in the hands or on the weight belt. Until the diver leaves the towline, the hands should not be used for anything but holding on. Sample bags, cameras, etc., should be attached to the towline with quick-release snaps. The amount of work to be accomplished and the equipment to be carried can be determined in predive practice.

Liveboating also can be used when surface-supplied umbilical systems are provided. Under such conditions, the speed of the boat must be slow (0.5-1.5 k (0.25-0.75 m/s)), carefully controlled, and determined by the experience of the divers. Precautions must be taken to avoid fouling the diver's umbilical in the propeller. Generally, the propeller is covered by a specially constructed wire or metal rod cage, and the umbilical is "buoyed" so that it floats clear of the stern. When liveboating from a large vessel, it may be desirable to tow a small boat behind the vessel and to tend the towed diver from the smaller boat. The tender must be especially cautious to keep the umbilical clear, and positive communications must be maintained between the bridge on the large vessel and the tender. The bridge also may wish to incorporate a system that allows monitoring of the diver's communication. If diver-to-surface communication is interrupted for any reason, the engines must be stopped.

8.10.2 Drift Diving

Drift diving is used occasionally to cover a large area when there are strong currents. Divers are put into the water upstream and drift with the boat, which trails a buoy with a clearly visible diver's flag. If the operation must be conducted in heavy currents, divers should enter the water as far upcurrent as necessary and drift with the current, holding onto a line attached to the drifting boat. Drift diving should be carried out only when observers in the drifting boat can see the diver's bubbles. If the drift involves a large vessel, a small boat should be used to track the divers and to pick them up. As with liveboating, drift divers should carry appropriate signaling devices (see Section 8.10.1).

During pickup, the boat operator should not (except in an emergency) approach the divers until the entire dive team is on the surface and has given the pickup signal. The boat's operator should bring the boat alongside the dive party on a downwind or downcurrent side, and the dive tender should assist the divers aboard. In all cases, the boat's motor should be in idle during pickup, with the propeller in neutral.

WARNING

Liveboating or Drift Diving Should Never Be Conducted With Inexperienced Personnel

8.11 UNDERWATER DEMOLITION AND EXPLOSIVES

Many underwater tasks require the use of explosives. Several different types of explosives are available, and these can be applied in a variety of ways. Because explosives are powerful and dangerous tools, they should be used only by trained personnel. To achieve accurate results in underwater applications, the explosive must be selected carefully and positioned properly.

Explosives are used under water to remove obstructions, to open new channels or widen existing ones, and to cut through steel, concrete, or wooden pilings, piers, or cables. They are also used to trench through rock or coral.

Explosives suitable for underwater use include primacord, various gelatins, plastics, precast blocks, and some liquids. Such charges are relatively safe to use if the manufacturer's instructions are observed and general safety precautions for explosives handling are followed. Bulk explosives (main charges) generally are the most stable of the explosive groups; there is progressively less stability with the secondary (primers) and initiator (detonators/blasting caps) groups. Initiators and secondary explosives always should be physically separated from bulk explosives.

WARNING

Only Properly Trained and Certified Personnel Are Permitted to Handle Explosives

An underwater explosion creates a series of waves that propagate in the water as hydraulic shock waves (the so-called "water hammer") and in the seabed as seismic waves. The hydraulic shock wave of an underwater explosion consists of an initial wave followed by further pressure waves of diminishing intensity. The initial high-intensity shock wave is the result of the violent creation and liberation of a large volume of gas, in the form of a gas pocket, at high pressure and temperature. Subsequent pressure waves are caused by rapid gas expansion in a noncompressible environment, which causes a sequence of contractions and expansions as the gas pocket rises to the surface.

The initial high-intensity shock wave is the most dangerous; it travels outward from the source of the explosion, losing its intensity with distance. Less severe pressure waves follow the initial shock wave very closely. For an extended time after the detonation, there is considerable turbulence and movement of water in the area of the explosion. Many factors affect the intensity of the shock wave and pressure waves; each should be evaluated in terms of the particular circumstances in which the explosion occurs and the type of explosive involved.

Type of Explosive and Size of the Charge. Some explosives have high brisance (shattering power in the immediate vicinity of the explosion) with less power at long range, while others have reduced brisance and increased power over a greater area. Those with high brisance generally are used for cutting or shattering purposes, while low-brisance (high-power) explosives are used in depth charges and sea mines, where the target may not be in immediate contact and the ability to inflict damage over a greater area is an advantage. The high-brisance explosives therefore create a high-level shock wave and pressure waves of short duration over a limited area. High-power explosives create a less intense shock and pressure waves of long duration over a greater area. The characteristics of the explosive to be utilized need to be evaluated carefully before use to estimate the type and duration of the resulting shock and pressure waves. The principal characteristics of the most commonly used explosives for demolition are shown in Table 8-4.

WARNING

Before Any Underwater Blast All Divers Should Leave the Water and Move Out of Range of the Blast

If a diver must remain in the water, the pressure of the charge a diver experiences from an explosion must be limited to less than 50 to 70 pounds per square inch (3.5-4.9 kg/cm^2). To minimize pressure wave effects, a diver should also take up a position with feet pointing toward the explosion and head pointing directly away from it. The head and upper section of the body should be out of the water, or divers should float on their back with their head out of the water.

For scientific work, very low-order explosions are occasionally used to blast samples loose or to create pressure waves through substrata. Each use must be evaluated in terms of diver safety and protection. Bottom conditions, the degree of the diver's submersion, and the type of protection available to the diver can

Table 8-4
Characteristics of Principal U.S.
Explosives Used for Demolition Purposes

Name	Principal Uses	Velocity of Detonation (meters/sec)	(feet/sec)	Relative Effectiveness as a Breaching Charge (TNT = 1.00)	Intensity of Poisonous Fumes	Water Resistance
Ammonium Nitrate	Demolition charge; composition explosives	2,700 mps	8,900 fps	---	Dangerous	None
PETN	Detonating cord; blasting caps; demolition charge	8,300 mps	27,200 fps	1.66	Slight	Excellent
RDX	Blasting caps; composition explosives	8,350 mps	27,400 fps	1.60	Dangerous	Excellent
TNT	Demolition charge; composition explosives	6,900 mps	22,600 fps	1.00	Dangerous	Excellent
Tetryl	Booster charge; composition explosives	7,100 mps	23,300 fps	1.25	Dangerous	Excellent
Nitroglycerin	Commercial dynamites	7,700 mps	25,200 fps	1.50	Dangerous	Good
Black powder	Time blasting fuse	400 mps	1,300 fps	0.55	Dangerous	Poor
Amatol 80/20	Bursting charge	4,900 mps	16,000 fps	1.17	Dangerous	Very poor
Composition A3	Booster charge; bursting charge	8,100 mps	26,500 fps	---	Dangerous	Good
Composition B	Bursting charge	7,800 mps	25,600 fps	1.35	Dangerous	Excellent
Composition C3	Demolition charge	7,625 mps	25,000 fps	1.34	Dangerous	Good
Composition C4	Demolition charge	8,040 mps	26,400 fps	1.34	Slight	Excellent
Tetrytol 75/25	Demolition charge	7,000 mps	23,000 fps	1.20	Dangerous	Excellent
Pentolite 50/50	Booster charge; bursting charge	7,450 mps	24,400 fps	---	Dangerous	Excellent

Source: U.S. Navy Operations Publication (1986) modify the effects of an explosion and must be considered in planning a dive involving the use of explosives. Divers also should be cautioned against diving in the vicinity when sub-bottom profiling using high-pressure air or high electrical discharges is being conducted.

8.12 UNDERWATER PHOTOGRAPHY

Scientists can use three methods to document underwater events: written records, tape recordings, and photography/television. This section describes the use of photography and television in underwater work.

Either diver-held cameras or remotely operated cameras can be used, and each has certain advantages. Diver-held cameras allow the photographer greater mobility and permit more precise positioning in relation to the subject than can be achieved with remotely controlled cameras. On the other hand, the remote camera disturbs underwater subjects less than the presence of a diver, and such cameras can operate at depths difficult for divers to reach.

8.12.1 Still Photography

8.12.1.1 Lenses and Housings

A 35-mm camera is a good starting point for underwater photography; cameras of this type can then be modified as necessary to meet task requirements. Two categories of camera can be used under water: instruments specifically designed to operate in the sea and that have water-tight sealing, such as the Nikonos®, or cameras designed for air use that are then housed in a watertight casing (Figure 8-20). Cameras designed for underwater use are easily portable and are relatively simple to use, while land-use cameras that have been adapted for underwater use are more versatile because they can be modified easily.

The choice of lens for any camera to be used under water is dictated by the required field of view and the clarity of the water. Because the distance from camera to subject must be short compared with that in air (Figure 2-5), a photographer who wishes to photograph a broad expanse must use a lens that has a wide degree of coverage. A good rule of thumb is that photographic visibility is only about one-third as good as eye visibility, which means that a wide-angle lens is an important tool even in clear water.

Wide-angle lenses create optical problems in underwater use. When used through a plane parallel port facing the water, these lenses produce distortions and color aberrations, narrow the angle of view, and lose sharpness at the periphery. The optical characteristics of water require that wide-angle lenses be corrected before they are used under water; a correction for underwater use can be designed into the lens formula (an expensive but effective approach), or corrective ports can be placed in front of the lens. Attaching a Plexiglas® dome (part of a hemisphere) and making an allowance for closer focusing of the lens than is necessary in air solves the underwater wide-angle lens

Figure 8-20
Underwater Cameras

A. Watertight Camera

Courtesy Nikon

B. Standard Camera in Watertight Housing

C. Motor-Driven and Motor Winder Camera in Watertight Housing

Courtesy Ikelite Underwater Systems

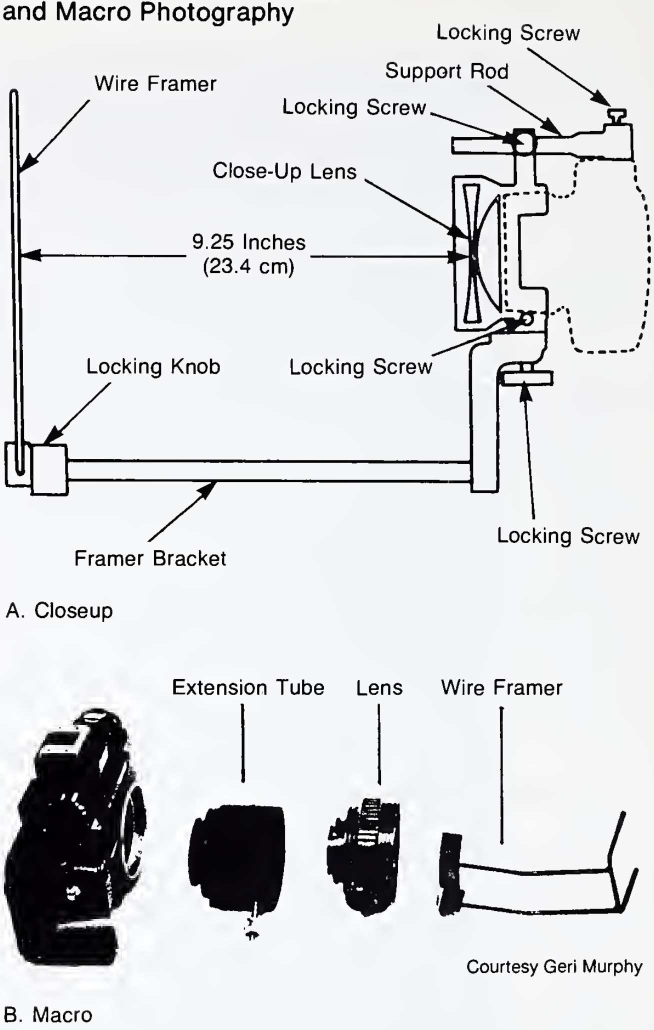
problem at lesser cost. Several commercial underwater housings have built-in corrective capabilities, and sealed cameras can be fitted with lenses that range from 15 to 80 mm in width.

When close-up photography of small objects is required, a plane parallel port coupled with lenses of longer focal length is useful. This type of photography demands ground glass focusing for precise framing, whisker sharpness of the image, a lens that can focus closely on the object, and at least one light source coupled to the camera. Plane parallel ports are helpful when using a longer lens because they enhance the telephoto effect without noticeably destroying the sharpness or color quality of the picture. For example, the use of a Nikonos® close-up kit with a standard 35 mm lens allows clear pictures to be obtained at a focal distance of 9.25 inches (23 cm); with the 35 mm lens alone, this distance must be 33 inches (84 cm). This ability is achieved through the use of an optically matched auxiliary magnifier lens that is placed over the primary lens.

Another method of obtaining close-ups is macro photography. This technique involves placing an extension tube between the camera's body and the lens to extend the focal length. A framer extension is attached in front of the lens to ensure proper framing and focal distance, which allows pictures to be obtained at distances as close as 2.5 inches (6.3 cm) from the subject. In addition to the high magnification, macro photography offers maximum color saturation, sharp focus due to the strong flash illumination, and minimal sea water color filtration because of the short focal distance (usually 3-7 inches (7.6-17.8 cm)). Figure 8-21 shows the basic equipment needed for closeup and macro photography.

Unmodified off-the-shelf underwater cameras or simpler housings for air cameras only permit a photographer-scientist to work in the mid-distance range; although useful data can be collected at this distance, long distance, closeup, and macro photography can provide valuable additional information. Well-designed and engineered housings for air cameras are heavier and bulkier and require more maintenance than sealed underwater cameras; however, housed cameras can be more flexible and have a broader range of wide angle and closeup capabilities than underwater cameras. Another disadvantage of sealed cameras is that the diver must work within a rigidly defined distance from his or her subject and must rely on mechanical framing rods to determine distance. Few fish will tolerate a metal framing rod in their territory, and these rods often cause unnatural behavior in fish and other marine life. In comparison, the ground glass focusing of the housed camera and its longer lenses allow photographers to work farther away from their subjects. The underwater photographer must weigh the advantages and disadvantages of each technique to determine which is most suitable. An excellent series of articles comparing closeup and macro photography was recently published in *Skin Diver* Magazine (Murphy 1987-1988).

Figure 8-21
Basic Equipment for Closeup and Macro Photography



A. Closeup

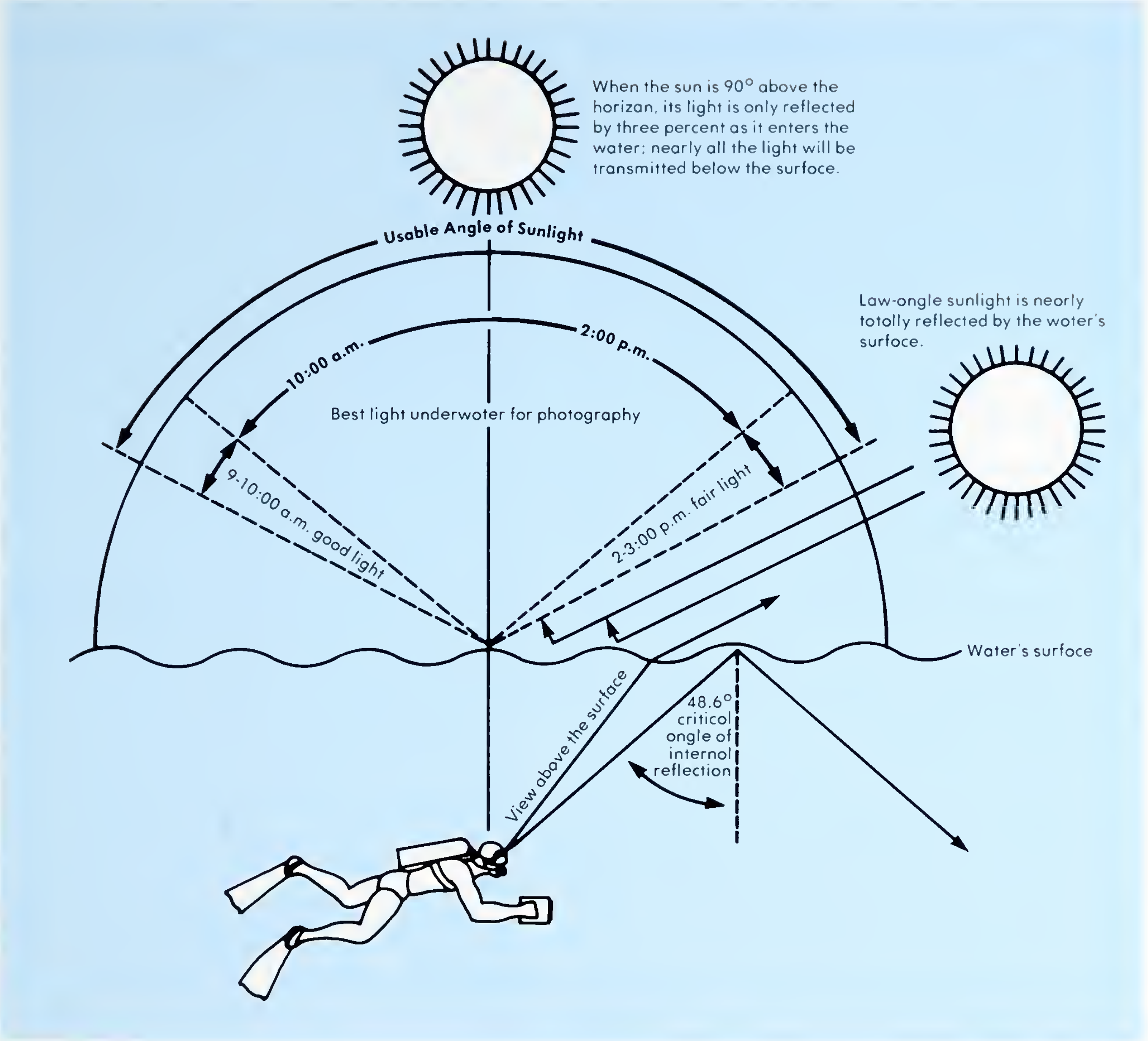
Courtesy Geri Murphy

B. Macro

8.12.1.2 Light and Color

Light and color go hand in hand in underwater photography (Figure 8-22). Color films balanced for either daylight or tungsten light are relatively blind to the color subtleties that the eye can distinguish within the blue and green spectra of water. When using available light in shallow depths, filtration offers some compensation. A color-correction filter (Table 8-5) over a lens will break blue color up enough so that a certain amount of color is restored. The color red disappears at approximately 22 feet (6.7 m), orange vanishes at

Figure 8-22
Diurnal Variation of
Light Under Water



Source: NOAA (1979)

approximately 40 feet (12.2 m), and yellow disappears at approximately 80 feet (24.4 m) of water, and no filtration of the lens can restore it (Figure 8-23). Color correction filters that selectively subtract ultraviolet light and correct the blue shift found in seawater are readily available (Murphy 1987). These filters, which are designed and color-balanced for available light at depths ranging from 15-50 feet (4.6-15.2 m), can be attached to and removed easily from the camera while under water. Because such filters subtract from the amount of light reaching the film, however, slightly longer exposure times are required when they are used (Murphy 1987). For additional information on the absorption and transmission of light under water, see Section 2.8.

Artificial light illuminates underwater situations and also brings out the color inherent in the subject. To be effective in water, artificial light must be used much closer to the subject than would be necessary in air. The closer and more powerful the light, the more it will compensate for the inherent blue of seawater. By varying distance and power, different balances can be obtained; a water-blue background with a slight hint of color can be achieved as easily as brilliantly illumi-

Table 8-5
Color Correction Filters

Underwater path length of the light (feet)	Filter	Exposure increase in stops
1	CC 05R	1/3
2	CC 10R	1/3
5	CC 20R	1/3
8	CC 30R	2/3
12	CC 40R	2/3
15	CC 50R	1

For distances of greater than 15 feet (4.5 m), composite filter with the appropriate number of filter units can be used.

Adapted from NOAA (1979)

nating the subject and completely obliterating the water quality.

Many good electronic flash units are made for underwater use. Some offer an underwater wide beam for use with wide-angle lenses, others a narrow beam that may penetrate the water column more effectively. (For a list of underwater strobe units, see Table 8-6.) The variance in exposure when using different strobe units is caused by:

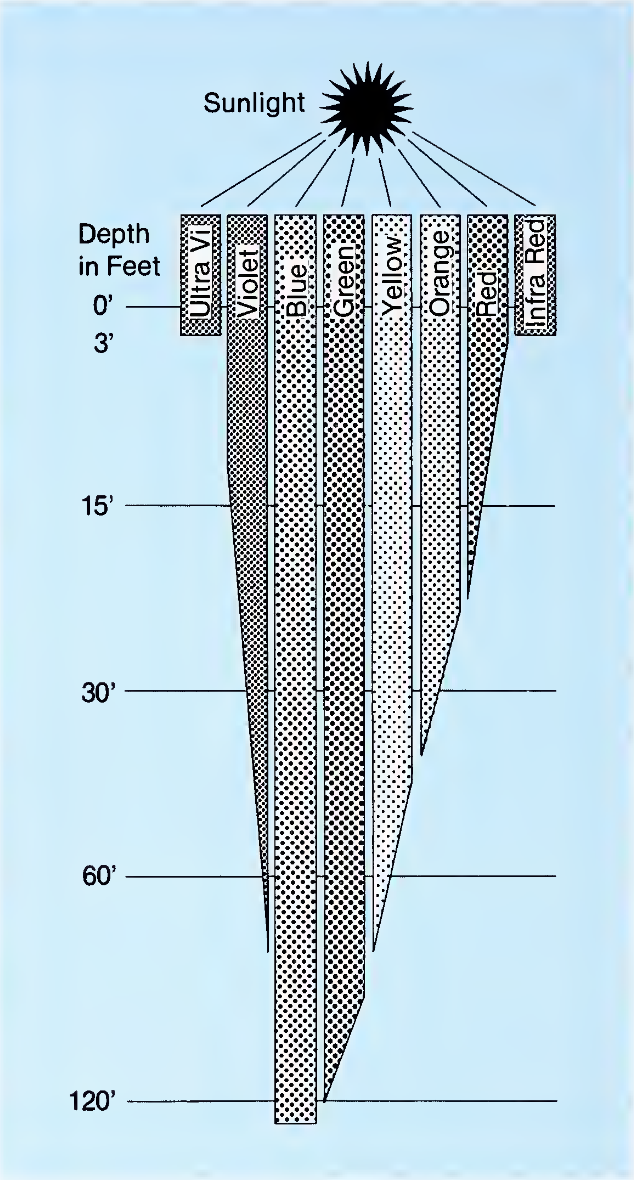
- The light beam angle;
- The strobe reflector material;
- The watt-seconds; and
- The guide number of the strobe.

Most strobes designed for underwater use come with an exposure guide (see Table 8-6).

When using macro photography under water, divers have a choice between manual and through-the-lens (TTL) flash systems. Although each has its advantages and disadvantages, the manual system is less expensive, has underwater quick-disconnect features, and offers better exposure control. In general, the manual system is the preferred flash method for macro photography. The automatic TTL system does, however, have some advantages. For example, because the length of the flash is controlled by the amount of light reflected from the subject back through the lens, the system automatically compensates for varying distances and reflectivity. This system also provides a visual signal confirming that the correct exposure was used. Automatic TTL systems can be switched readily to the manual mode as needed; Table 8-7 lists some TTL mini strobes that are suitable for macro photography.

Tests should be made before the dive to establish correct exposures with any unit that uses films of various speeds. It is advisable when shooting with available light to use shutter speeds of 1/100 or 1/125 of a second, if possible. These shutter speeds should freeze the action and reduce the amount of blur caused by movement of the camera during exposure.

Figure 8-23
Selective Color Absorption
of Light as a Function of Depth
in Clear Ocean Water



Derived from Church 1971
Derived from Church (1971)

Table 8-8 lists exposure compensations for underwater photography that should be used as a starting point for work with adjustable cameras. These recommendations are based on the following conditions: bright sunshine between 10 a.m. and 2 p.m., slight winds, and underwater visibility of about 50 feet (15.2 m). The degree of visibility, the amount of particulate matter in the water, the reflective qualities of the bottom, and other factors can significantly affect photographic results, and thus it is important to conduct tests before

Table 8-6
Manual and Through-the-Lens (TTL) Strobes for Closeup Photography

Mfg.	Model	Head Size	Weight In Air	Depth Tested	Beam Angle	Beam Spreader	Color Temp.	Batteries	Power Modes	No. of Flashes	Recycle Time	U/W Guide	Slave Mode	TTL Mode
Akimbo	Subatec S-100	6 x 3.5"	2.75 lbs.	500 ft.	96	No	4,500 K	Removable Rechargeable Pack	1 1/2 1/4 1/8	150 250 350 500	4 sec. 3 sec. 2 sec. 1 sec.	22 16 11 8	No	No
Akimbo	Subatec S-200 TTL	6 x 3.5"	2.75 lbs.	500 ft.	96	No	4,500 K	Removable Rechargeable Pack	1 1/2 1/4 1/8	150 250 350 500	4 sec. 3 sec. 2 sec. 1 sec.	22 16 11 8	No	Yes
Berry Scuba	Whale Strobe TTL II	7 x 4"	2.3 lbs.	165 ft.	65	Yes (95)	5,600 K	4 AA Dry Cells	Full 1/4	130 450	7 sec. 2 sec.	32 16	No	Yes
Helix	Aquaflash 28	6 x 5"	3.8 lbs.	165 ft.	65	Yes (95)	5,600 K	6 AA Dry Cells	Full 1/4	80 300	10 sec. 1 sec.	40 22	Yes	No
Helix	Aquaflash 28 TTL	6 x 5"	3.8 lbs.	165 ft.	65	Yes (95)	5,600 K	6 AA Dry Cells	Full 1/4	80 300	10 sec. 1 sec.	40	Yes	Yes
Ikelite	Substrobe 150 TTL	10 x 6"	7 lbs.	300 ft.	110	No	4,800 K	Removable Rechargeable Pack	Full 1/2 1/4	150 300 600	6 sec. 3 sec. 2 sec.	22 16 11	Yes	Yes
Ikelite	Ikelite 225 TTL	10 x 6"	8 lbs.	300 ft.	110	No	4,800 K	Removable Rechargeable Pack	Full 1/2 1/4	125 250 500	6 sec. 3 sec. 2 sec.	32 22 16	Yes	Yes
Nikon	SB-103	7 x 4"	2 lbs.	160 ft.	65	Yes (95)	5,500 K	4 AA Dry Cells	Full 1/4 1/16	130 450 1,400	12 sec. 4 sec. 1 sec.	24 12 5.6	No	Yes
Nikon	SB-102	8.5 x 5.5"	4.3 lbs.	160 ft.	79	Yes (95)	5,500°K	6 C Dry Cells	Full 1/4 1/16	120 400 1,200	14 sec. 5 sec. 2 sec.	33 16 8	Yes	Yes
Oceanic	3000 Master	9 x 5.7"	4.8 lbs.	300 ft.	110	No	5,700 K	Built-in Rechargeable Pack	High Low	350 650	3 sec. 1 sec.	22 16	Yes	Yes
See & Sea	YS-150	9.5 x 5"	5.4 lbs.	350 ft.	100	No	5,400 K	Removable Rechargeable Pack	Full 1/2	100 200	5 sec. 3 sec.	22 16	Yes	No
See & Sea	YS-100 TTL	6 x 4"	2 lbs.	200 ft.	65	Yes (80)	5,400 K	4 AA Dry Cells	Full 1/2 1/4 1/8	130 250 450 900	12 sec. 12 sec. 12 sec. 12 sec.	32 22 16 11	Yes	Yes
Graflex Subsea	Subsea Mark 150RG	11 x 6"	8.5 lbs.	350 ft.	150	No	5,500 K	Removable Rechargeable Pack	150 100 50	175 250 325	5 sec. 3 sec. 2 sec.	22 16 11	Yes	No

Courtesy Geri Murphy

starting to photograph; these variables can cause exposures to vary by as much as 4 or 5 stops (see Section 2.8.1.3).

Although most underwater photographers now use strobe flash systems, flash bulbs (clear bulbs for distance and blue bulbs for closeups) can still be used effectively under water (Table 8-9). The longer water column effectively filters the clear bulbs with blue so that the light balances for daylight film. Divers should be aware that the pressure at great depth can cause bulbs to implode; divers have been cut when changing bulbs in deep water.

Incandescent lights that are powered either by battery or by a topside generator and that are a must for motion picture work can also be used in still photography. Incandescent light does not penetrate water as

Table 8-7
Through-the-Lens (TTL) Mini Strobes for Automatic and Manual Exposure

Mfg.	Model	Head Size (diameter)	Beam Angle (degrees)	Beam Spreader	Color Temp.	U/W * Guide No.	Batteries	Manual Power Modes	Recycle ** Time (seconds)	No. Flashes	Extras	Depth Tested (feet)
Berry Scuba	**Whale Strobe** TTL II	**7 x 4”**	**65**	**Yes** (95 degrees)	**5,600** K	32	4 AA	Full 1/4	7 2	130 450	• Confirm Signal • Test Fire	165
Helix	Aqua Flash 28 TTL	6 x 5”	70	Yes (95 degrees)	5,600 K	40	6 AA	Full 1/4	10 1	80 300	• Slave • Confirm Signal • Test Fire	165
Ikelite	Substrobe MV	4.5 x 3.5”	65	No	5,800 K	20	4 AA	Full	5	250	• Inter-changeable sync cords	300
Nikon	SB-103 Speedlight	7 x 4”	65	Yes (95 degrees)	5,500 K	24	4 AA	Full 1/4 1/16	12 4 1	130 450 1,400	• Confirm Signal	160
Sea & Sea	YS-100 TTL	6 x 4”	65	Yes (80 degrees)	5,400 K	32	4 AA	Full 1/2 1/4 1/8	12 12 12 12	130 250 450 900	• Slave • Audio Ready • Exposure Calculator	200
Sea & Sea	YS-50 TTL	6 x 3”	72	No	5,400 K	22	4 AA	Full	10	140		200

*U/W Guide Number based on ISO 50 film with strobe set on full power manual.
**Recycle times and number of flashes based on alkaline batteries. Rechargeable nickel-cadmium batteries produce faster recycle times but fewer flashes.

Courtesy Geri Murphy

Table 8-8
Exposure Compensation for Underwater Photography

Depth of Subject	Number of f-Stops to Increase Lens Opening Over Normal Above-Water Exposure
Just under surface	1 1/2 f-stops
6 feet (1.8 m)	2 f-stops
20 feet (6.0 m)	2 1/2 f-stops
30 feet (9.0 m)	3 f-stops
50 feet (15.0 m)	4 f-stops

Adapted from NOAA (1979)

well as electronic or flash bulb light, and these lights are also clumsier to use.

Lighting arms and brackets or extension cords allow off-camera light to be placed in many positions (Figure 8-24). Lights should not be placed on the camera lens axis, because lighting suspended particles in the water directly can curtain off the subject matter and increase backscatter. Underwater exposure meters, primarily of the reflected-light type, are manufactured with brackets that permit them to be either mounted or hand held.

8.12.1.3 Selection of Film

Depending on the quality of the documentation required by the diver/scientist, a wide variety of both black-and-white and color films is available (Table 8-10). The sensitivity of film is measured according to an American Standards Association (ASA) rating that ranges for most purposes from 25 to 400 ASA. There are slower and extra high-speed emulsions available for special purposes and techniques.

Film is merely a base on which an emulsion of light-sensitive, microscopic grains of silver halide has been placed. These particles react to light in various ways that affect the following:

- **Grain,** which is the clumping of silver halides. High-speed film clumps more rapidly than slower film, and enlargements show graininess more than small pictures. Grain tends to destroy the sharpness and detail of a photograph, but it can be reduced or increased in processing. To obtain sharp pictures, film of the finest grain should be used, unless the light is insufficient and a high-speed film is necessary.

Table 8-9
Underwater Photographic
Light Sources

Type of Lighting	Depth Limit (ft)	Factors Limiting Visibility	Accuracy of Color Rendition	Ability to Light Subject for the Human Eye as Camera Will See It	Control of Effects From Light Scattering	Duration (sec)	Intensity	Means of Determining Exposure	Power Requirement	Extent of Use	Remarks
Natural	50 to 100	absorptivity, scattering	poor (predominantly green)	very good	fair to good	continuous	good at surface, but decreases with depth	meter	none	general	—
Flood	none	absorptivity, scattering	fairly good	very good	very good	continuous	relatively low	guide number determined by experiment	high (1/2 to 2 kw)	general, especially at greater depths	—
Flash bulbs	none	absorptivity, scattering	fairly good	poor	fair	1/50 to 1/100	high	guide numbers	self-contained battery	general	Diver must replace bulbs
Electronic flash	none	absorptivity, scattering	fairly good	poor	fair to very good	1/1,000 to 1/2,000 or faster	very high	guide numbers, automatic	self-contained battery	general	Electronic flash is probably better than regular flash for use under water

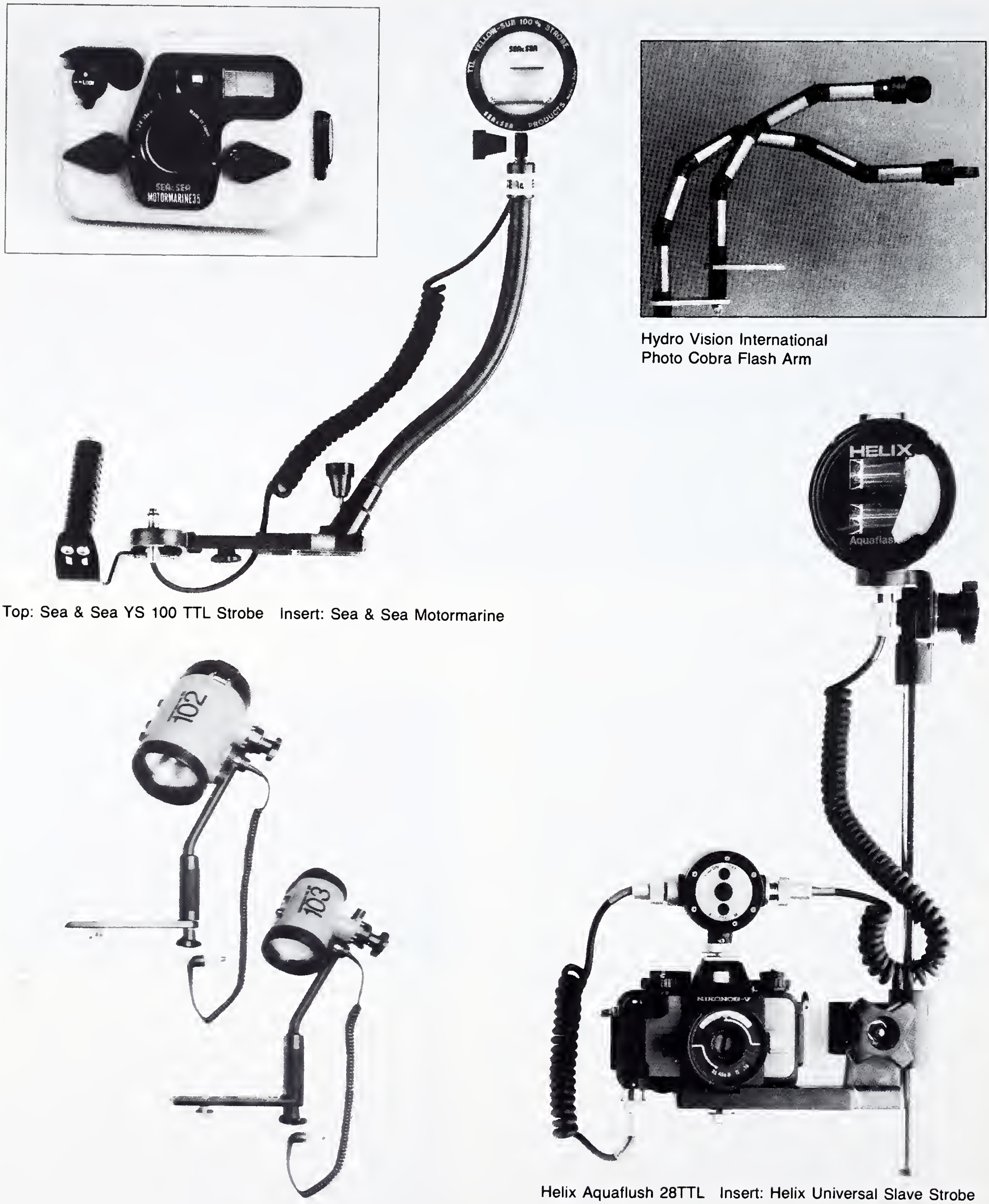
Adapted from NOAA (1979)

- **Resolving power,** which is the ability of the film to hold fine details; resolving power is measured in the number of lines per millimeter that the film will record distinctly. It is related directly to grain: the finer the grain, the higher the resolving power.
- **Latitude** is the over- and under-exposure tolerance of a film. Wide-latitude film is best under water because a picture can be obtained even when the exposure is not exact. For example: black-and-white negative film will allow sufficient exposure with a 4 f-stop variance, while color transparencies of short latitude will tolerate only a 1/2 f-stop deviance. A wide-latitude film should be used whenever a good picture is necessary and bracketing is impractical. Color negative films, which are used to make color prints, offer better latitude than color reversal films, which are used to produce color slides.
- **Color balance,** which is a problem only of color film. Films are made to match the color temperatures of different light sources--daylight, tungsten, strobe, etc. Processing and printing greatly affect the ultimate color balance. Both color reversal and color negative films are daylight films; both are color-balanced for outdoor use in sunlight and for use with electronic flash systems.
- **Contrast** is the difference in density between darkest shadow and brightest highlights. Under water, contrast is low because of the diffused light. For best results, film with high contrast should be used under water.
- **Color reversal.** Color reversal (positive color) film is used most commonly for still work under water. Slides or black-and-white or color prints can be made from this film, and the resulting picture can be viewed in its true perspective shortly after the film is developed.
- **Storage and shelf-life.** The storage and shelf-life of film is often an important consideration. For example, over the counter films can withstand relatively high storage temperatures but may shift color with aging. Professional films, however, remain constant in color but must be stored under temperature-controlled conditions.

A fast film, such as Eastman Kodak Ektachrome film that has an ASA value of 200, can produce very acceptable results, with good depth of field at moderate light levels. In low light conditions, the effective ASA value may be increased four times to ASA 800, although this film speed requires special processing (see Table 8-11). Black-and-white films are available that can be processed to achieve an ASA of 1200. As higher ASA's are approached, however, black-and-white films lose shadow detail during developing.

When taking underwater pictures with a flash or strobe, both the f-stop generated by the strobe or flash and the available light (f number registered on the light meter) must be considered. In this case, the aperture must be adjusted to accommodate the stronger of the two light sources or a flash distance must be selected that will equalize the natural and artificial light levels.

Figure 8-24
Lighting Arms and Brackets
for Strobe Systems



Top: Sea & Sea YS 100 TTL Strobe Insert: Sea & Sea Motormarine

Hydro Vision International
Photo Cobra Flash Arm

Nikonos Speedlight SB-102 and SB-103

Helix Aquaflush 28TTL Insert: Helix Universal Slave Strobe

Courtesy Sea & Sea, Hydro Vision International, Nikonos®, and Helix

Table 8-10
Still Films Suited
for Underwater Use

Film Type	Daylight ASA	Description	Sharpness	Grain	Resolving Power
		Daylight Color			
Eastman Kodak Ektachrome 64 Daylight	64	A medium-speed color slide film for general picture-taking purposes, e.g., macro, closeup, flash, available light	high	very fine	high
Eastman Kodak Ektachrome 200 Daylight	200	A high-speed color slide film for general picture-taking purposes (e.g., deep available light)	high	very fine	high
Eastman Kodak Ektachrome 400 Daylight	400	A very high-speed color slide film for general picture-taking purposes (e.g., deep available light)	—	—	—
Eastman Kodak Kodachrome 25 Daylight	25	Moderate speed, daylight balanced (e.g., macro photography)	high	extremely fine	high
Eastman Kodak Kodachrome 64 Daylight	64	A medium-speed color slide film for general picture-taking (e.g., closeup, flash, available light)	high	extremely fine	high
Eastman Kodak Kodachrome 400 Daylight	400	A very high-speed color slide film for general picture-taking (e.g., deep available light)	—	extremely fine	very high
Vericolor II S	100	Professional color negative film for short exposure times (1/10 sec. or shorter)	—	—	—
		Black and White			
Panatomic X	32	Slow-speed film for a very high degree of enlargement	very high	extremely fine	very high
Plus-X Pan	125	Medium-speed film for general purpose photography where a high degree of enlargement is required	very high	extremely fine	high
Tri-X Pan	400	Fast, general purpose film when the degree of enlargement required is not great	very high	very fine	medium
Verichrome Pan	125	Medium-speed film for general purpose photography where a high degree of enlargement is required	very high	extremely fine	high

Note: Proper color balance occurs when colors are reproduced as they actually are. Making warmer or colder tones is an aesthetic decision of the cameraman. All color films should be exposed properly and have good color acceptability at ± ½ stop. At more than ± ½ stop, color reproduction differs noticeably from the original color.

Adapted from NOAA (1979)

Infrared film has opened up new possibilities in underwater photography; however, because of drastic color changes, infrared film is not suitable for scientific color documentation. Kodak recommends starting at ASA 100, but underwater tests have shown that ASA 50 exposed at 1/60 sec at an f-stop of 5.6 on a sunny day in 20 feet (6.1 m) of water will give proper exposure. A yellow filter should be used to exclude excessive blue saturation.

8.12.1.4 Time-Lapse Photography

Many biological and geological events occur so slowly that it is neither possible nor desirable to record them

Table 8-11
Processing Adjustments
for Different Speeds

Kodak Ektachrome 200 Film (Daylight)	Kodak Ektachrome 160 Film (Tungsten)	Kodak Ektachrome 64 Film (Daylight)	Kodak Ektachrome 50 Professional (Tungsten)	Change the time in the first developer by
800	640	250	200	+ 5½ minutes
400	320	125	100	+ 2 minutes
Normal 200	Normal 160	Normal 64	Normal 50	Normal
100	80	32	25	— 2 minutes

For Kodak Ektachrome film chemicals, Process E-6.

Adapted from NOAA (1979)

continuously on film. Time-lapse photography, which permits the scheduling of photographic sequences, is the solution in such cases. This technique has been used widely for years for studying plant growth, weather patterns, and many other phenomena. It is particularly useful for underwater studies, where, in addition to investigating slow processes, the inconvenience and cost of frequent site visits make other photographic techniques impractical.

Modern technology has greatly improved underwater camera systems that are triggered automatically by means of standard timing devices or by remote command. The time-lapse interval (the time between photographs) is determined by the nature of the event being studied, the available equipment, environmental conditions, and cost. The time interval can vary from seconds or minutes to hours or even days. An example of a long-term study using current technology is the record being made of the scouring and erosion of sand around offshore platforms and pipeline installations during storms in the North Sea. In this instance, three pictures per day were taken over a period of 1 month, using a stereo-camera system (Photosea Systems Inc. 1984).

Because time-lapse systems remain unattended for long periods, they must be thoroughly checked out for reliability, leaks, buoyancy, and anchoring before deployment. They must also be maintained and stored carefully when not in use.

8.12.2 Motion Picture Photography

Almost all motion picture cameras can be adapted for underwater use; such cameras should be confined in rugged, reliable underwater housings that will withstand rough handling. All camera controls should be outside the housing and should be as simple as possible. The camera also should be balanced properly to be neutrally buoyant. The underwater cinematographer must position the camera himself or herself and must be able to swim in and out of scenes with as little unnecessary movement as possible.

To cover a single subject adequately, several dives should be planned. An average for topside shooting in good amateur work is 1:5 (1 foot (0.3 m) used for every 5 feet (1.5 m) exposed). Photographers should consider using a tripod if the objects to be photographed are generally in one area. Artificial lighting is critical for motion picture work deeper than approximately 30 feet (9.1 m). Surface-powered lights are cumbersome but more reliable and longer-lasting than battery-powered lights. Ideally, a buddy diver should handle the lights, which frees the photographer to concentrate on filming techniques.

8.12.2.1 Selection of Film

A wide range of motion picture film is available for underwater photography in both 100 foot (30.5 m) and in 400 foot (121.9 m) rolls (see Table 8-12). Eastman Color Negative Film 7291 should yield the best picture information in both highlight and shadow portions of the film. This film also has a broad range of color correctability that can be applied during printing and is faster and has more latitude than Eastman Ektachrome Commercial 7252. Eastman 7294 also is used frequently for filming at greater depths and on darker days because it has a higher ASA rating, it can be processed as easily as 7291 can, and it has a fine quality that allows it to be edited with 7291 scenes. Eastman Video News films 7239, 7240, and 7250 are improvements over Eastman Ektachrome EF (daylight) 7241 and Eastman Ektachrome EF (tungsten) 7242, both with respect to speed and warmer tone (highlight) characteristics, which lend a pleasing overall effect to the photographs.

8.12.2.2 Procedures

Because all film is sensitive to heat, it should not be stored in the sun or in hot enclosures. In addition, film should always be loaded in subdued light. Other pro-

Table 8-12
Motion Picture Films
Suited for Underwater Use

Film Type	ASA	Description
Black and White		
Reversal Eastman Plus-X 7276	50 Daylight	A medium-speed panchromatic reversal film characterized by a high degree of sharpness, good contrast and excellent tonal gradations
Reversal Eastman Tri-X 7278	200 Daylight	A high-speed panchromatic reversal film that provides excellent tonal gradations and halation control
Reversal Eastman 4-X 7277	400 Daylight	A very high-speed panchromatic reversal film
Negative Eastman Plus-X 7231	80 Daylight	A medium-speed panchromatic negative film for general production
Negative Eastman Double X 7222	250 Daylight	A high-speed panchromatic negative film representing the latest advances in speed granularity ratio
Negative Eastman 4-X 7224	500 Daylight	An extremely high-speed panchromatic negative film
Color		
Reversal Eastman Ektachrome Commercial 7252 (Tungsten)	Daylight 16 w/85 filter	A color reversal camera film designed to provide low-contrast originals from which color release prints (duplicates) of good projection contrast can be made
Reversal Eastman Ektachrome EF 7241 (Daylight)	160	A high-speed color reversal camera film, balanced for daylight exposure, intended primarily for direct projection (after processing). However, satisfactory color prints can be made if they are balanced properly
Reversal Eastman Ektachrome EF 7242 (Tungsten)	w/85 filter = 80	A high-speed color reversal camera film balanced for tungsten exposure, intended primarily for direct projection (after processing). However, satisfactory color prints can be made if they are balanced properly
Reversal Eastman Ektachrome Video News 7239 (Daylight)	160	A high-speed color reversal camera film balanced for daylight exposure, intended for use under low-level illumination both for color news photography and for high-speed photography. Satisfactory color prints can be made if they are balanced properly
Reversal Eastman Ektachrome Video News 7240 (Tungsten)	w/85 B filter = 80	A high-speed color reversal film, intended for use in daylight. Satisfactory color prints can be made if they are properly balanced
Reversal Eastman Ektachrome Video News High Speed 7250 (Tungsten)	w/85 B filter = 250	No data
Negative Eastman Color Negative II 7291 (Tungsten)	w/85 filter = 64	A high-speed color negative camera film designed for use in tungsten light and in daylight with an appropirate filter. It is characterized by accurate tone reproduction, excellent image structure, and wide exposure latitude. Excellent prints (duplicates) can be made from the original

Adapted from NOAA (1979)

cedures to be observed when taking motion pictures are:

- When using 16-mm equipment, photographers should film at 24 frames per second (FPS) to achieve real-time action. At 24 FPS, most motion picture cameras attain a shutter speed of approximately 1/50 of a second. Such a shutter speed is necessary for interpreting f-stops when using an exposure meter.
- When starting to film, the housed camera should be put in the water, taken down to 30 fsw (9.1 m), returned to the surface, and checked for leaks.
- The camera should be held as steadily as possible; if feasible, a tripod (custom-made or commercially bought and heavily weighted) should be used.
- Photographers should overshoot at the beginning and end of each scene to establish the scene and to aid in the editing process.
- The length of scenes should be varied (some short, some long); this can be done in editing, but film can be saved if the value and length of each scene are considered during the shooting.
- Different distances, angles, and exposures of each scene should be shot.
- Scenes should not be rushed because the beauty of the sea can be lost if the photographer is hurried.
- Only a few special effects should be used, and then only when they are exceptional and an integral part of the picture.
- The shooting script should generally be followed, but it is important to be flexible enough to deviate from it if the situation so dictates.
- Photographers should know their cameras thoroughly so that they can be used most effectively.

8.12.3 Special Procedures

Underwater photographers may find the following hints helpful:

- Overweighting with plenty of lead makes a diver a much steadier photographic platform.
- A wet suit protects against rock and coral injuries even when it is not needed for thermal protection.
- Photographic equipment should not be suspended from lines on boats in a rough sea unless the line has a shock absorber incorporated into it.
- To the extent possible, photographic sequences should be planned before the dive.
- Cameras should be taken down to a habitat open unless the housing has a relief valve; pressure prevents cameras from opening at depth. The camera housing should be taken up open, regardless of relief valves, because the housing can flood when external pressure is released.
- A basic tool kit should be set up for camera maintenance, and spare parts (0-ring grease, WD 40 or equivalent, towels. etc.) should also be on hand.
- Wearing a wool watch cap can keep water from the diver's hair from dripping into the camera during reloading.
- Protective shock-absorbing cases lined with foam rubber are essential for transporting photographic gear in a boat.
- Actual underwater experience and experimentation are often more informative than photography books, many of which contain errors.
- If a camera floods in salt water, the best immediate action is to pack the equipment in ice and to keep it frozen until it can be delivered to a repair facility. If ice is not available, the camera should be flushed thoroughly by immersing it in fresh water or alcohol.
- At the end of the day's work, all camera equipment should be washed with fresh water.
- When the camera and housing are removed from the water, they should be placed in the shade immediately; this is especially true in the tropics, where even a minimal exposure to the sun can cause heat inside the camera housing to damage the film.

8.13 UNDERWATER TELEVISION

Significant advances continue to be made in underwater television systems. These advances offer great promise for the scientific and working diver with respect to recording natural phenomena, conducting surveys, documenting experimental procedures, ship hull inspection, damage assessment, improving working procedures and techniques, and diving safety. Excellent solid-state underwater color systems now are on the market that permit small, compact television cameras to be: (1) held in the hand, (2) mounted on tripods, (3) worn as an integral part of a diving helmet (Figure 8-25), (4) mounted on manned submersibles, or (5) used as an integral part of remotely controlled systems. Underwater video systems capable of operating at depths as great as 35,000 feet (10,668 m) are now available. This capability, when coupled with the high quality of current video systems, has resulted in television replacing photography as the method of choice for underwater scientific and technical documentation.

When selecting an underwater video system, it is best to choose a system designed specifically for underwater operation rather than to select a "surface"

Figure 8-25
Video Recording Systems

A. Handycam® System With Underwater Housing

Courtesy Sony Corp. of America

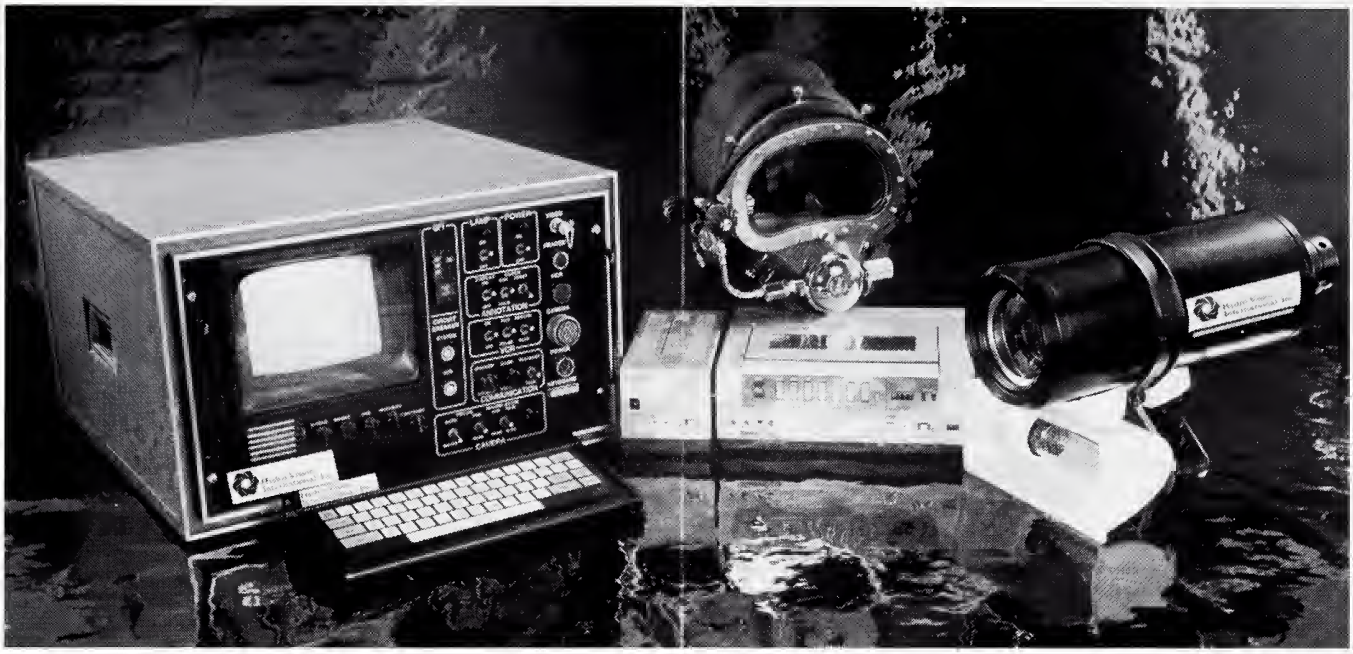
B. Underwater Housing With Angle Lens Attached

Courtesy Ikelite Underwater System

C. Diver Using Underwater Video System

Photo by Jim Church

Figure 8-26
Commercial Underwater
Video System



Courtesy Hydro Vision International, Inc.

system packaged for underwater use. Surface television cameras normally operate at high light levels and often are not sensitive enough for underwater conditions. Further, surface cameras are sensitized to red light, while underwater cameras for use in the open sea have maximum sensitivity in the blue-green region of the spectrum. The dynamic range of an underwater camera also is critical if it is to be used effectively under the broad range of light intensities commonly encountered.

To achieve these underwater needs, specifically designed low-light-level television cameras often are used; such cameras can record images at light levels as low as 0.0005 foot-candle at the camera tube while maintaining a horizontal resolution of 500 lines. In addition to operating at low light levels, these cameras can significantly extend the viewing range. Such systems offer great potential for working under conditions of low visibility, where the diving scientist needs to observe or record the behavior of marine life without either artificial light or the veiling effect of backscatter that occurs with lighted systems. In addition to the optical characteristics of video cameras, other important features to consider include: size, weight, and buoyancy control; type of viewfinder; automatic versus zone focusing; automatic exposure control with manual override; and automatic white balance. Other options to consider are built-in microphones, zoom lenses, focusing for macro photography, housings, and general ease of operation.

The selection of a lighting system for underwater television filming is just as critical (and often as expensive) as the selection of a camera. Although quartz iodide lights are often used for underwater work, their lights are not as efficient as mercury or thallium discharge lamps because quartz provides a high red spectral output that is absorbed rapidly in seawater. On the other hand, quartz iodide light is the only source that produces enough red to allow good underwater color filming. Another alternative is a water-cooled quartz halogen lamp that offers burn times of up to 3 1/2 hours at 100 watts at depths to 250 feet (76 m). Like cameras, underwater lights are designed to operate at depths of several thousand feet (i.e., several hundred meters). Specific factors to consider when selecting a lighting system for a video camera include the size and location of the battery pack, burn and recharge times, the size of the underwater beam angle, and an arm and bracket mounting system. Rapid advances continue in the development and miniaturization of videotape formats. Miniature camcorders weighing less than 3 pounds (1.4 kg) have reduced the bulk of video systems and permitted the use of high-quality 8 mm video tapes.

Underwater TV systems can operate from 12 volts DC, 115 vac, or 230 vac input power, which provides the flexibility to operate either from large or small diving support platforms. As with other television systems, data can be viewed in real time on the surface or be stored for later viewing. The combination of a diver-held or helmet-mounted camera, a surface-based monitor, and a good diver-to-surface communication system permits the diver to act as a mobile underwater platform under the direction of the diving supervisor or a scientist on the surface. This arrangement not only permits real-time recording of events but greatly enhances diving safety by allowing the surface support team to monitor the activities of the diver continuously. This monitoring can be done either at the site on the surface or at a remote station or laboratory.

Computer microprocessing technology also permits digital displays to be overlaid on the output of the video camera. For the diving scientist, this means that a wide variety of data can be recorded, including information on such things as environmental conditions, weather, water conditions, and the results of experiments.

Underwater TV is used in a variety of modes, including (1) attached to submersibles, (2) lowered by cable for use as a remote instrument, or (3) placed on or near a structure or habitat for long-term monitoring. Within working depth limitations, divers may be asked to attach, detach, or service a TV camera in the monitoring mode or to carry the camera-light module. The best results are obtained when the camera is manipulated by a diver using either umbilical diving gear with hard-wire communications or a scuba diver with reliable wireless communication. In either case, the diver's narrative is recorded on videotape, along with the picture.

Commercial systems are available that are designed as an integral unit, including a full face mask, helmet-mounted or hand-held camera, monitor, and complete facilities for two-way communications and videotaping (Figure 8-26). Divers usually can work with cable lengths up to 500 feet (152.4 m) if floats and buoys are used to reduce the drag and the possibility of fouling. Underwater television technology has reached the stage where it is preferable, in most cases, to underwater photography. Its advantages include: on-the-spot evaluation of results; instant replay; communication with surface support personnel both for safety and assistance in the evaluation of results; and cost-effective duplicate films.

SECTION 9 PROCEDURES FOR SCIENTIFIC DIVES

PROCEDURES FOR SCIENTIFIC DIVES

9

9.0 GENERAL

Diving is widely performed to observe underwater phenomena and to acquire scientific data, and this use of diving has led to significant discoveries in the marine sciences. In some instances, diving is the only method that can be used to make valid observations and take accurate measurements. Using equipment and techniques designed specifically for underwater use, the diving scientist can selectively sample, record, photograph, and make field observations. Some research, such as ecological surveys, benthic inventories in shallow water, and fish behavior studies, requires diving to be used throughout the entire project, while other research may require diving only as an adjunct to submersible, remote sensing, or surface ship surveys. Regardless of the project or the role that diving plays, marine research using diving as a tool has been important in understanding the ocean, its organisms, and its dynamic processes.

The diving scientist or technician's working time is measured in minutes and seconds instead of hours (unless the saturation diving mode is used). Long underwater work periods necessitate decompression times twice as long as the actual work time on the bottom: the cost-effectiveness of scientific diving therefore depends on how efficiently scientists can perform their tasks. Efficiency under water requires good tools, reliable instruments that can be set up rapidly, and a well-thought-out task plan. Until recently, there was almost no standardization of the equipment and methods used to perform scientific research under water, and in many cases the instruments, tools, and techniques were (and still are) improvised by individual scientists to meet the specific needs of the project. However, now that the value of scientific diving has been widely recognized, scientists are becoming concerned about the accuracy and replicability of their data and results and are increasingly using statistically valid and standardized methodologies. Through necessity, scientists who want to work under water must be proficient both in their scientific discipline and as divers, inventors, and mechanics.

The purpose of this section is to describe some of the procedures used in diver-oriented science projects. These methods are intended as guidelines and should not be construed as the best or only way to perform underwater surveys or to gather data.

9.1 SITE LOCATION

To study any region carefully, it is necessary to plot on a base map the precise location from which data will be obtained (Holmes and McIntyre 1971). This is especially important if there is a need to return to the same location several times during a study. The scale of the base map depends on the detail of the study and the size of the area to be investigated. In geological mapping of the seafloor, a scale of 1 inch to 200 yards (2.5 cm to 183 m) is adequate for reconnaissance surveys. In archeological and some biological studies, a much more detailed base map, with a scale of 1 inch to 30 feet (2.5 cm to 9 m), may be required. If existing charts do not contain the proper scale or sounding density, it may be necessary to use echosounder survey techniques to construct a bathymetric map of the bottom before starting the dive. Gross features can be delineated and bottom time used more efficiently if the diver has a good bathymetric map of the study area. If published topographic charts are inadequate, the sounding plotted on original survey boat sheets of a region (made by NOAA's National Ocean Service) can be contoured and will usually provide adequate bathymetric control for regional dive surveys. If the survey plan requires bottom traverses, it will be necessary to provide some means of locating the position of the diver's samples and observations on the base chart.

Techniques used to search for underwater sites fall into two general categories: visual search techniques and electronic search techniques. The results from the latter must be verified by divers after the specific site has been located.

9.1.1 Traditional Methods

The great majority of diving is carried out in nearshore waters where surface markers, fixed by divers over strategic points of the work site, may be surveyed from the shore using well-established land techniques, including the theodolite, plane table, and alidade, or from the sea, using bearings from a magnetic compass or, preferably, measuring horizontal angles between known points with a sextant. Small, inexpensive, and rugged plastic sextants are commercially available, and techniques for using them are simple to learn. Although sextants have limitations, especially when they are used from a small boat, they are generally sufficiently accurate to be useful.

At the other extreme in terms of complexity is a site relocation method used successfully by many scientists; in this method, lineups and landmarks on shore are sighted visually, without the use of artificial aids. Basically, once the site is located and the boat anchored over it, scientists take a number of sightings of various nearshore landmarks (such as trees, hills, and power poles) and align them visually so that when the boat is repositioned the landmarks line up the same way. The only drawbacks to this method are that the work must be conducted near shore and the visibility must be good in order for the shoreside landmarks to be seen. When several lineups have been established and proven, they should be diagrammed in a notebook that is kept in the boat. These methods allow divers to establish the locations of major features in the working area accurately. If buoys are used for location, particular care is needed to ensure that the surface floats used during the initial survey lie directly over the weights anchoring them to the selected underwater features; the best plan is to wait for a calm day at slack tide.

In some cases it may be advisable to leave the seabed anchors in place after the floats have been cut away. If this is contemplated, the anchors should be constructed to rise slightly above the surrounding terrain so that they may be seen easily on the next visit. Small floats made of syntactic foam may be tied to the anchors below the surface with a short length of polypropylene line to aid in relocation. However, because biological fouling soon obscures any structure used, expensive, highly painted markers generally are not appropriate. Floating markers, even if they are small and badly fouled, usually can be seen if they protrude a short distance above the surrounding substrate. Once the transect, grid, or other system of markers is established and fixed relative to permanent features on the shore, the diver should record the position of selected features within the working area in relation to the buoy array.

9.1.2 Electronic Methods

Electronic positioning methods are excellent, but they are also expensive. If cost is no object or extreme accuracy of station positioning and marking is required, several highly sophisticated electronic ranging instruments may be used. Satellite positioning equipment can position a scientist within a few meters of the desired location. Loran equipment, although less accurate, is readily available at relatively low cost.

9.2 UNDERWATER SURVEYS

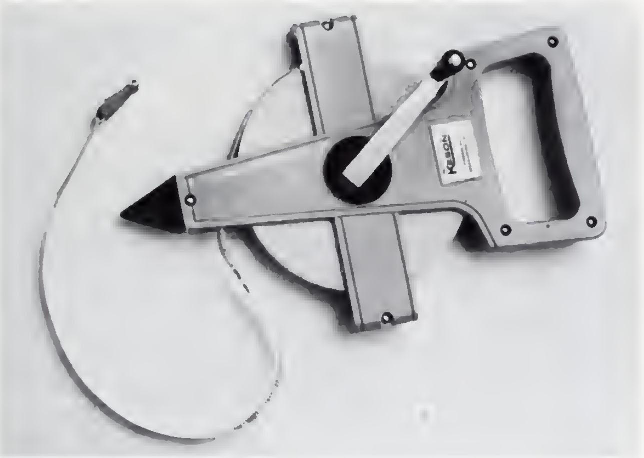
A variety of methods is used to survey the underwater landscape; these include direct and indirect surveying methods. Direct methods require diver-scientists to measure distances themselves, while indirect approaches use photography or acoustic means to determine distances, angles, and other features.

9.2.1 Direct Survey Methods

With the exception of long distance visual triangulation, many of the methods used in land surveying can also be used under water. A review of a standard college text on surveying will provide the scientist with some basic surveying concepts, while Woods and Lythgoe (1971) give an excellent description and review of methods that have been devised specifically for work under water. In most diving surveys, distances are measured with a calibrated line or tape. However, measurements done under water seldom need to be as accurate as those on land, and the use of an expensive steel tape is unnecessary. Additionally, most ropes or lines will stretch and should be used only if the measurement error resulting from their use is acceptable. A fiberglass measuring tape that has a minimum of stretch and is marked in feet and inches on one side and meters and centimeters on the other is commercially available (see Figure 9-1). These tapes come in an open plastic frame with a large metal crank to wind the tape back onto the reel. They are ideal for most purposes and require no maintenance except for a fresh water rinse and lubrication of the metal crank. No matter what measuring method is used, especially if long distances are involved, the lines or tapes must be kept on reels to prevent tangling or fouling. In clear waters, optical instruments can and have been used to measure both distance (range finder) and angles between objects for triangulation.

The first step in surveying any area is to establish a horizontal and vertical control network of accurately located stations (bench marks) in the region to be mapped. Horizontal control is the framework on which a map of features (topography, biology, or geology) is to be constructed; such a control provides a means of locating the detail that makes up the map. Vertical control gives the relief of the region and may be obtained by stadia distance and vertical angles or by spirit leveling. Rough measurements can be made by comparing differences in depth using a diver's depth gauge, but measurements may be inaccurate if the irregular sea surface is used as the reference point.

Figure 9-1
Fiberglass Measuring Tape



Courtesy Forestry Suppliers, Inc.

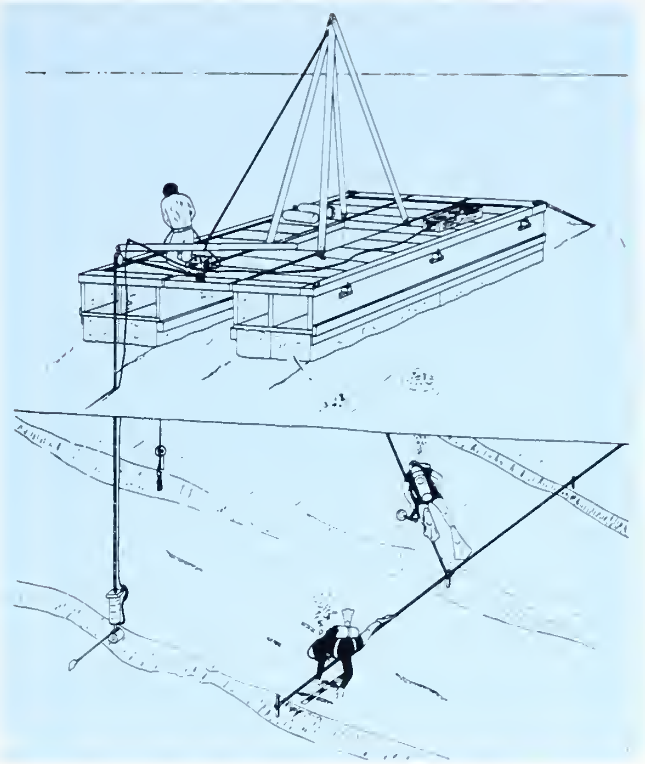
One method that has worked well in areas of high relief where echosounders are not satisfactory is described below (Hubbard 1978).

- Along a convenient axis (N-S, E-W, etc.), place two permanent poles, one on either end of the survey area.
- Stretch a line between them to serve as a fixed centerline.
- At intervals prescribed by the size of the area and the irregularity of the terrain, place additional poles identified by some sort of coding. The use of a taut-line buoy may make the sites more visible.
- Lay out the lines perpendicular to the centerline by using the centerline poles as tie-in points. If a permanent grid is desired, place poles at intervals comparable to those between the centerline poles. If the terrain has significant relief, horizontal changes can be measured by moving away from each centerline pole, as shown in Figure 9-2.
- In areas of significant terrain, it is difficult to maintain an accurate horizontal measurement. Knowing the difference in depth (y) between the two points (from a calibrated depth gauge or several depth gauges) and the measured slope distance (z), the horizontal distance (x) can be calculated easily using the formula:

$$x = \sqrt{z^2 - y^2}.$$

When using a depth gauge over a period of hours, tidal fluctuations must be taken into account. A reference staff or bench mark should be established at the beginning of the survey, and readings should be taken at the reference during the period over which depths are being measured in the survey area. By going in either direction from each of the centerline poles, a complete bathymetric survey can be conducted with considerable accuracy.

Figure 9-2
Bottom Survey
in High-Relief Terrain



Source: NOAA (1979)

Determining the two end points of the centerline by the methods described in Section 9.1.1 locates the site with respect to surface positions.

The detail to appear on the finished map is located by moving from the control networks (bench marks) to the features to appear on the finished map. On some surveys, the control is located first and the detail is located in a separate operation after the control survey has been completed. On other surveys, the control and the detail are located at the same time. The former method is preferable if long-term observations are to be carried out in an area, for example, around a permanently established habitat. The latter technique is preferable if reconnaissance studies are being made in remote regions or in areas that will not require the re-establishment of stations.

9.2.2 Indirect Survey Methods

Indirect underwater surveying involves techniques that do not require the diver physically to measure angles and distances using tapes, lines, protractors, etc. Indirect underwater surveying currently is performed using either photographic or acoustic methods.

9.2.2.1 Underwater Photographic Surveys

Obtaining reliable measurements by means of photography—photogrammetry—though not as advanced under water as on land—is a tool being used with increasing frequency. Limited visibility is one of the major drawbacks in its application.

Photographs with appropriate scales in the field of view can be useful in measuring objects on the seafloor and in recording changes with time. Subtle changes often recorded on sequentially obtained exposures of the same area or station can be missed if memory alone is relied on.

Photographic transects are useful in showing variations over an area or changes that occur with depth. In the past, little true photogrammetry was conducted because of the technical difficulties in producing corrected lenses and maintaining altitude and constant depth and because of the high relative relief of many bottom features. However, improved techniques have been developed that allow increased accuracy and flexibility. Recent computerization of photogrammetric plotting equipment has reduced technical difficulties considerably.

To improve mapping for detailed archeological studies, photographic towers may be used (Bass 1964, 1968; Ryan and Bass 1962). The progress of excavation in each area can be recorded with grid photographs taken through a hole in the top of the tower. This approach produces a consistent series of photos that can be compared easily when analyzing the data. The tower ensures that each photo is taken from the same point of view, thus simplifying follow-on dark room procedures. A photograph is, however, a perspective view that requires correction for the difference in scale and position of objects.

A series of stereophoto pair photographs may be taken of sites for three-dimensional viewing under a stereo-viewer. More important, it is possible to make three-dimensional measurements from such photos.

The use of wide-angle lenses, such as a 15-mm lens, permits detailed photographs to be taken that cover large areas from short distances. Bass (1978) recommends that rigid metal grids be constructed and divided into 6.6 foot (2 m) squares. These squares are then excavated and photographed individually.

9.2.2.2 Underwater Acoustic Surveys

Another method for conducting bottom surveys involves the use of sonic location beacons (pingers). These devices are particularly useful if there is a need to return to specific locations. The system may consist of small (the size of a roll of quarters) pingers, which can be placed at the site of interest, and a diver-held receiver. The pingers can be tuned by the diver to specific frequencies to differentiate between sites.

More complex and costly systems can be used to avoid some of the problems that arise with these simpler methods. A high-frequency sonic profiler (Figure 9-3) can rapidly measure underwater sites (Dingler et al. 1977). Such a device, however, requires electronic and technical support beyond the means of most researchers. If cost is not a factor, the sonic profiling method is by far the best way of obtaining an accurate representation of small-scale subaqueous bed forms.

Acoustic Grid. This method of underwater survey is the acoustic equivalent of direct trilateration. In its simplest form, three acoustic transponders are placed at known positions on the sea bottom. These transponders are interrogated sequentially from within their established grid, and the time delay before each response occurs is measured and recorded. If the velocity of sound in seawater is known for that area and time, the delay in time can be related to the distance between the interrogator and each of the transponders.

Transponders are implanted and their positions are determined using direct underwater survey methods. The interrogator is a small, hand-held directional sonar device that has a digital readout of the time delay. The diver, positioned above the point to be surveyed, aims visually at the first transponder and takes three readings. The process is repeated for the other two transponders. Ideally, the data are sent to the surface via an underwater communications link. In the absence of this equipment, the data should be recorded on a writing slate attached directly to the interrogator. The accuracy of this system can be increased significantly by using four or five transponders.

Because so many variables affect the velocity of sound in seawater, errors in measurement can have a significant effect on the resulting mathematical analysis. For example, sound velocity measurements in very shallow water can be affected seriously by errors in recording temperature. Accurate results depend on keeping the salinity and temperature measurement errors small enough so that the errors in velocity are below the inherent equipment-introduced errors.

More sophisticated versions of the acoustic grid survey system are available, and many of these read out range directly. Although more convenient to use, system inaccuracy may still be created by variability in speed of sound. Compact and reasonably priced sound velocimeters are now available that permit in-situ measurements to be used immediately as survey system correctors.

The acoustic grid is particularly valuable when a site is visited repeatedly to measure features that vary over time, such as the motion of sand waves. Another advantage of this system is its internal completeness. If the geodetic location of the site is not important and

Figure 9-3
High-Frequency
Sonic Profiler

Photo Tom Harman

only relative position and motion within the site are to be measured, the acoustic grid is an appropriate method. It is also possible to relate the grid measurements to a geodetic map at a later time.

Phase Measurement. Unlike the acoustic grid method, which determines the position of an object relative to a fixed network of transponders, phase measurement systems are contained within the support ship except for a single mobile transponder. Three receiving elements are located precisely with respect to each other on the underside of the support craft; they are usually attached to a mast extended over the side of the craft. A diver places a transponder on the object whose position is to be determined, and an interrogator located on the ship queries the transponder. A phase analysis is performed by the receiver on the return signal, which is displayed as deflection angle and line-of-sight range to the object with respect to the receiver element mast. The only variable is velocity of sound, which must be determined by the method discussed previously.

Small transponders are available that can be strapped to a scuba cylinder so that the position of the diver can be monitored continuously by personnel in the support craft. When continuous communication is available, the diver can be directed through a geodetically fixed survey pattern if the ship's position is known accurately.

This system is suited to applications where a large area must be surveyed or where there are only one or two sites of interest. Although the system has the disadvantage of requiring a surface-support platform, its inherent mobility and flexibility are distinct advantages except in situations where job requirements make the acoustic grid or one of the direct methods preferable.

Under certain conditions, the phase measurement system can be more fully utilized if diver towing techniques are employed. In this case the position of the diver relative to the support ship must be monitored continuously, which increases both ease of operation and accuracy. Combining the phase measurement system with a good diver-to-surface communication system results in an excellent survey procedure.

9.3 UNDERWATER RECORDING METHODS

The simplest and most widely used method for recording data under water involves using a graphite pencil on a white, double-sided plastic board. These records are sufficiently permanent to withstand normal handling during a dive. Since most divers use abbreviations and shorthand in recording observations and species names, however, the notes should be transcribed as soon as possible. Wax pencils are usually not satisfactory because they become brittle and break in cold water, and pencil holders have metal parts that will corrode. Ordinary pencil lead can be cleaned off easily with scouring powder, but wax smears and often must be removed with a solvent. Mechanical pencils are unsatisfactory, since the metal parts will soon corrode. The best writing instrument is an off-the-shelf, readily available plastic pencil that uses bits of sharpened lead encased in plastic butts.

Slates can be made multipurpose by adding compasses, rulers, or inclinometers (see Figure 9-4). Because there is a risk of misinterpreting the often rather erratic notes made under water, a list of tasks to be undertaken and the form to be used for all measurements should be developed before the dive. These lists and tables may be inscribed on the plastic pads. In some cases it is desirable to retain the original records (this is particularly important in the case of archeological drawings, for instance); drawings then are made with wax crayons on waterproof paper attached to the plastic board by screws or rubber bands. There are several types of underwater paper, including a fluorescent orange paper. Standard formats can be duplicated ahead of time to facilitate recording during a dive. A simple and inexpensive technique for underwater data sheets is to prepare the sheets on regular typing paper and then have each sheet laminated in the same way that drivers' licenses and other important identification are preserved.

Where precise measurements are to be made, it is good practice for two observers to take independent

Figure 9-4
Multipurpose Slate

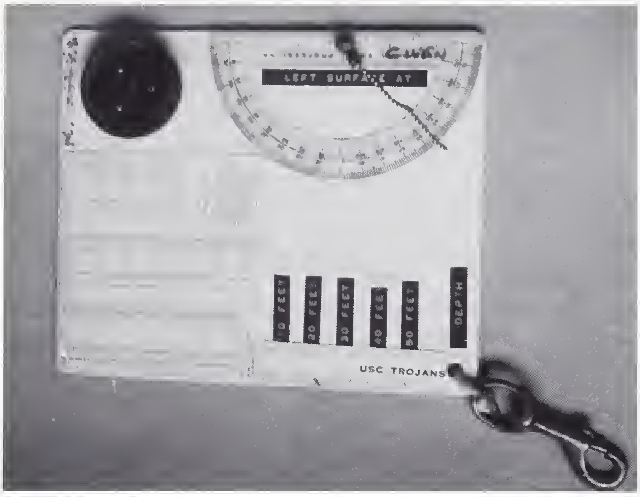


Photo Robert Dill

measurements and to check them with each other for agreement before returning to the surface. If there is disagreement, the measurements should be repeated.

Tape recording is another useful, although somewhat specialized, method of documenting data under water. The most satisfactory and reliable system includes a cassette tape recorder as part of the hardwire two-way communication system used in umbilical diving; the alternative is a self-contained unit carried by a diver in the scuba mode. The position of the microphone and the way in which it is waterproofed is critical in determining the usefulness of an underwater tape recorder.

Some commercial systems feature a special mouthpiece unit into which a microphone is built and to which the scuba regulator is attached. Standard mouthpiece bits, however, do not allow the lips to move sufficiently to form anything more than simple words or noises, which are usually intelligible only to the speaker immediately after the recording is made. This is especially true for biologists giving long lists of scientific names or for scientists reading numbers from instruments.

NOTE

The most critical factor to consider in a voice-recording system for data gathering is the ability of the diver to speak and enunciate clearly enough to be understood and transcribed accurately.

The best equipment configuration is a full-face mask, equipped with a microphone that is located away from the immediate mouth area; this position diminishes breathing noise and increases voice fidelity by picking up sounds from the resonating chamber formed by the mask rather than from the high-sibilance area in front of the lips. Several commercially available masks are equipped with demand regulators that can be used with standard scuba cylinders or with an umbilical air supply. When an umbilical is used, most diver-tender communications systems can be wired to accept a tape recorder so that both sides of the conversation can be recorded. Regardless of the unit selected, divers should practice using the system in shallow water until they can produce intelligible transcriptions routinely.

To optimize recording fidelity and minimize distortion and interference, cassette tapes of the highest quality should be used. At present, commercial tapes are available that have 60 minutes of recording time on each side, and this capacity is generally sufficient for most scuba missions. Maintenance is especially important for tape recorders; special care must be taken (checking O-rings, seals) to prevent corrosion.

9.4 BIOLOGICAL SURVEYS

Biological surveys generally have the same requirements and involve the same techniques as those described in Section 9.2; however, some specific aspects should be mentioned. Biological surveys are used for many purposes, including determining the environmental impact of placing man-made objects on the seafloor and assessing the effects of ocean dumping on marine resources. In most marine environments, it is not possible to evaluate the impact of man-made changes without performing special baseline surveys designed to obtain specific information about the biota and the physical environment. To be meaningful, these studies must be made before structures are emplaced on the seafloor or material is discharged into the area. When baseline information cannot be obtained before the natural undersea environment has been altered by human actions, biological surveys can be used to determine the incremental impacts of subsequent activities.

Baseline studies must be designed so that they can be monitored at prescribed intervals. Control stations placed outside the area being studied are necessary to provide data on environmental changes occurring naturally (e.g., seasonal effects).

The techniques of underwater biological surveying involve establishing a standardized methodology to make the results of the survey quantitatively meaningful and ecologically acceptable. This is done by choosing stations at specific depth intervals along a transect line and dropping an anchor at each station to serve as the center of a circle of study. Quantitative observations are then made within the circle; general bottom topography and biological features of the areas beyond the circles are also noted.

The amount of bottom area covered does not need to be the same for every station; water clarity and the complexity of the biota will affect the size of the study circle. The poorer the visibility, the more restricted the amount of bottom that can be surveyed. In West Coast regions and for sand stations having a limited macrobiota, a 10.2 foot (3.1 m) line is generally used to produce a 323 square foot (30 m^2) area of study. In rocky areas, where the biota is more diverse, a 7.2 foot (2.2 m) line can be used to define the radius of the circle of study. In addition, using tools such as plankton nets and bottom cores, scientists can estimate the number of plants and animals, take quantitative samples of life forms, and take photographs of general bottom conditions and of each quadrat.

Environmental factors that must be considered when surveying the establishment and growth of underwater communities include exposure to wave or swell action, type and slope of substrata, water temperature, dissolved oxygen and nutrient content, and extent of grazing. Variations in the intensity and spectral composition of light under water also have a significant effect on plant communities, but it is often difficult to obtain accurate light measurements. The illumination at or within a given plant community can be obtained with accuracy only by actual in-situ light measurements; photographic light meters are not satisfactory for this purpose. Underwater spectroradiometers, which are probably the most effective means of measuring light in the sea, are available. Submersible spectroradiometers have been used in studies of photosynthesis and calcification rates of corals.

Most underwater investigators have used transect or simple quadrat methods for the analysis of benthic communities. A reasonable description of the change in biota relative to depth and other factors can be obtained by measuring the area of cover along a strip or band transect. Accurate quantitative data on standing crops can best be obtained by collecting the entire ground cover from a quadrat and sorting this into component species in the laboratory for subsequent analysis.

9.4.1 Estimating Population Densities

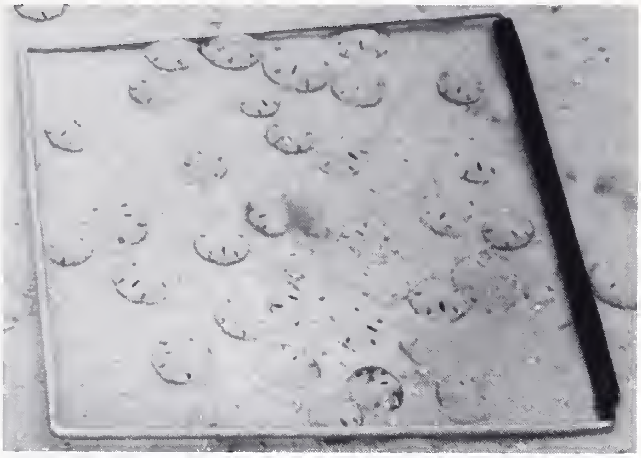
When estimating the biological content or density of a given region, it is necessary to take surface area into account. An irregular surface can greatly increase the area; to the extent that the surfaces sampled depart from the horizontal, area will be underestimated, which will cause density to be overstated. This bias becomes particularly important as the scale of the surface variation approaches the scale of the distribution being measured. Dahl (1973) describes a technique designed to quantify the estimation of irregular surfaces in the marine environment. Briefly, the technique consists of making some simple height, frequency, and surface length measurements and then applying a surface index formula to determine the surface area. The technique has been applied to coral reefs, benthic algal substrata, Thalassia, sand and rubble zones, reef crests, and patch reefs.

A simple method for estimating populations of sessile organisms is described by Salsman and Tolbert (1965), who used it to survey and collect sand dollars (Figure 9-5). At each location sampled, the authors spent 10 to 15 minutes making observations, taking photographs, and sampling population density. To facilitate counting and to ensure a random sample, a counting cell was constructed by bending an aluminum rod into a square 11.8 inches (30 cm) long on each side. Inexpensive counting squares also can be constructed using PVC tubing. As divers approached the seafloor, they released the square, allowing it to fall to the bottom. The organisms within this square were counted and collected for later size determination; this procedure was then repeated at least two more times at each location sampled. The same method can be used to take a random sample of any sessile organism.

A device used for surveying epifauna is the diver-operated fishrake (Figure 9-6). It has been used to obtain information on the small-scale distribution patterns and estimates of population densities of demersal fishes and invertebrates. The apparatus consists of a metal tubular frame fitted with a handle, a roller of rigid PVC tubing into which stainless steel wire "staples" are fixed, and an odometer made of a plastic tracking wheel and removable direct-drive revolution counter. It is pushed along the bottom by a diver who makes visual counts, size estimates, and other observations on animals that occur within the path traversed by the roller.

In some underwater situations involving observations of animal behavior, it is necessary to remain a reasonable distance from the subject so as not to interfere with normal behavior. Emery (1968) developed an underwater telescope for such situations by housing a rifle scope in PVC tubing with acrylic plastic ends. The underwater scope described by this author functioned satisfactorily at depths as great as 180 feet (55 m). An underwater telephoto camera lens was used during the *Tektite II*

Figure 9-5
Counting Square for Determining Sand Dollar Density



Courtesy U.S. Navy

experiments to avoid interfering with animal behavior (VanDerwalker and Littlehales 1971).

At the other end of the magnification continuum is an underwater magnifying system (Pratt 1976). This device, referred to as the Pratt Macrosnooper, has a magnification power of seven and permits the diver to study marine organisms too small to be comfortably observed with the naked eye. It is a three-element lens system designed specifically for use under water and consists of three lenses with appropriate spacers inserted into a 2 inch (5 cm) plastic pipe (see Figure 9-7). Holes are then drilled through the housing and the spacers to permit the entry of water for equalization at depth. When in use, the Macrosnooper is held against the mask faceplate. It should be cleaned and rinsed carefully, along with other diving equipment, after each use. Soap, mineral, or fungus deposits, which may be removed by an overnight soak in either bleach, vinegar, or laundry detergent, may form on the lenses after prolonged use.

9.5 BIOLOGICAL SAMPLING

Although a discussion of research design for a sampling program is outside the scope of this volume, careful attention should be given to the implementation of sampling methods. Chapters on the design of sampling programs can be found in Holmes and McIntyre (1971).

As Fager and his colleagues have noted (Fager et al. 1966),

> Underwater operations have several advantages over sampling from the surface for ecological studies involving quantitative sampling or observations of behavior. Probably the most important practical one is the ability to observe the sampling apparatus in operation, to make estimates of its effectiveness, and to improve the design or procedure *in situ*. In some cases, such as with small demersal fish, underwater sampling is considerably more effective than from the surface. Direct observation gives one a feeling for the types and magnitudes of the errors associated with the sampling and allows one to decide whether the sampling site is unusual or representative of a larger area. With the less common species, it may be particularly important to be able to make repeated population estimates without imposing unnatural mortality by the removal of individuals.

Figure 9-6
Diver-Operated Fishrake

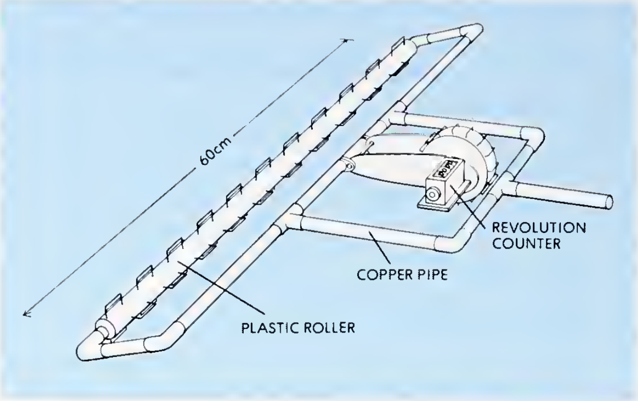


Photo Art Flechsig

Because a diver using marker buoys, stakes, or pingers can return repeatedly to the same location, changes in both environment and the biota can be followed for considerable periods. In addition, changes can be imposed on the environment by selective removal of species, by alteration of substrata, and so on, and the effects of these experimental manipulations can be followed in detail.

9.5.1 Plankton Sampling

Planktonic organisms that live within 3.2 feet (1 m) of the bottom can be sampled with a skid-mounted multilevel net apparatus that is pushed by a diver over a predetermined distance. Hand-operated butterfly valves are used to isolate the collection bottles located in the cod end of the net.

Plankton sampling nets 11.8 inches (30 cm) in diameter, with a mesh size of 0.08-0.12 inch (2-3 mm) are used to collect plankton selectively in reef areas.

Figure 9-7
Underwater Magnification System

A. Optical System

B. Complete System

Photo Harold Wes Pratt

Air-filled bottles also can be inverted in appropriate areas to suck up plankton and water samples.

Several methods of sampling plankton have been developed. Ennis (1972) has employed a method using two diver propulsion vehicles on which a 19.7 inch (50 cm) plankton net was mounted. A similar method was used during a saturated dive in the *Hydrolab* habitat at Grand Bahama Island, when two 3.2 foot (1 m) long Hensen egg nets were mounted on a single diver propulsion vehicle that was operated at a speed of about 2 to 3 knots (1 to 1.5 m/s) (Figure 9-8). At the end of every run, each net should be washed separately and the sample should be concentrated into the cod end by holding the net up inside a trapped bubble of air under a plastic hemisphere having an 18 inch (45.8 cm) radius. The cod end should then be removed, and the contents of the net should be poured into a glass jar. The jar should be filled, except for a small volume at the top, with filtered seawater, and plastic wrap should be placed over the top of the jar to trap a small bubble of air. The jar is then removed from the hemisphere and carried to a work area at the base of the habitat. The work area should be deeper than the hemisphere so that hydrostatic pressure will help to keep the air bubble from escaping. A syringe filled with formalin is then pushed through the plastic wrap, the jar is capped, immediately secured, and labeled. When this procedure is carried out properly, there is no sample loss. Before a net is reused, it should be turned inside out and backflushed.

Figure 9-8
Hensen Egg Nets Mounted on
a Single Diver Propulsion Vehicle

Photo William L. High

9.5.2 Benthic Organism Sampling

Quantitative sampling of the epifauna can be accomplished by counting the animals within a randomly located circle or square quadrat. A circle template, fixed center rod, and movable arm may be constructed of brass, with the center rod and movable arm marked with grooves at 0.4 inch (1 cm) intervals (Figure 9-9). The position of an animal within the circle can be defined by three numbers: the distance along the center rod from a standard end; the distance from the center rod along the movable arm; and the half of the circle within which the animal was observed. To study details of the distribution pattern of individuals of sedentary species, the "distance of the nearest neighbor" technique can be used. This method involves preassembling a large, lightweight metal or PVC square and dropping it at the appropriate location. Within the square, divers place short brass or plastic rods with fabric flags on them at predetermined positions in relation to the individuals of the species being examined. After the positions of all individuals have been marked, distances to nearest neighbors are measured, and reflexives are counted.

Samples of the substrate and infauna can be collected with no loss of sediment or organisms by using a simple coring device with a widemouth sample container (a jar) attached to the top (Figure 9-10). The corer is pushed a given distance, e.g., 2 inches (5 cm), into the sand, tipped slightly, and an aluminum plate is slipped under it through the sand. The apparatus is inverted and the sediment is allowed to settle into the jar. Once all sediment and organisms are inside the jar, the coring attachment is removed and the jar is capped.

Figure 9-9
A Circle Template for Determining
Benthic Population Density

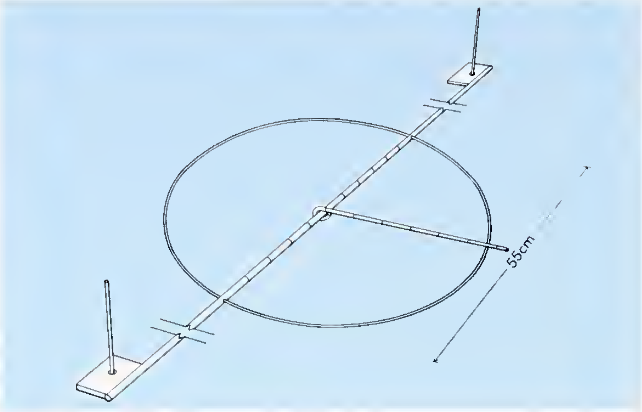


Photo Art Flechsig

Another simple soft-bottom sampling device, especially good for small infauna and meiofauna, is a thin-walled coring tube of transparent plastic, the diameter of which is based on a predetermined sample designed to gather the desired substrate and organisms most efficiently. Most organisms obtained by this type of device will be found in the top 3.9 to 4.7 inches (10 to 12 cm) of the sample. For ease of handling, the tube should be at least 11.8 inches (30 cm) long and sealed with rubber corks, one of which has a small hole drilled through it. With both corks off, the tube should be rotated carefully into the sand to the desired depth, and the cork with the small hole should then be used to cap the tube. While gripping the tube for removal, the scientist's thumb should be held over the hole to create a suction that keeps the sediment from falling out. When the tube is free of the sediment, the bottom cork should be inserted. Samples accurate to any depth can be taken with this device, and depth lines can be marked on the outside of the tube. To remove the core, the scientist places a finger over the hole in the top cork, removes the bottom cork, and allows the plug to fall out. To remove discrete segments of the core, the plug may be pushed out the end and cut into desired lengths or quick-frozen in dry ice immediately upon surfacing (to prevent migration of animals) and later cut with a hacksaw.

A multilevel corer is used for studying the depth distribution of infauna. This corer samples an area of about 1 inches square (45 cm^2) to a depth of 2.4 inches (6 cm). The corer consists of a square brass box fitted with a funnel adapter at the top to accept widemouth sample containers. The front side of the corer is slotted to permit thin metal slide plates to be inserted to separate the sample into five separate layers, which can then be transferred under water to separate sample containers.

Figure 9-10
Coring Device
With Widemouth Container

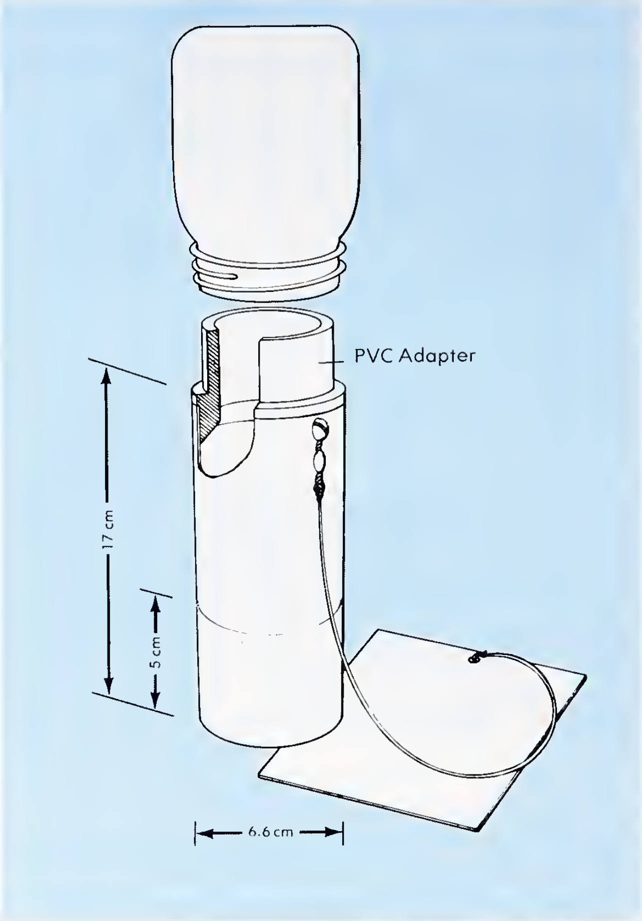
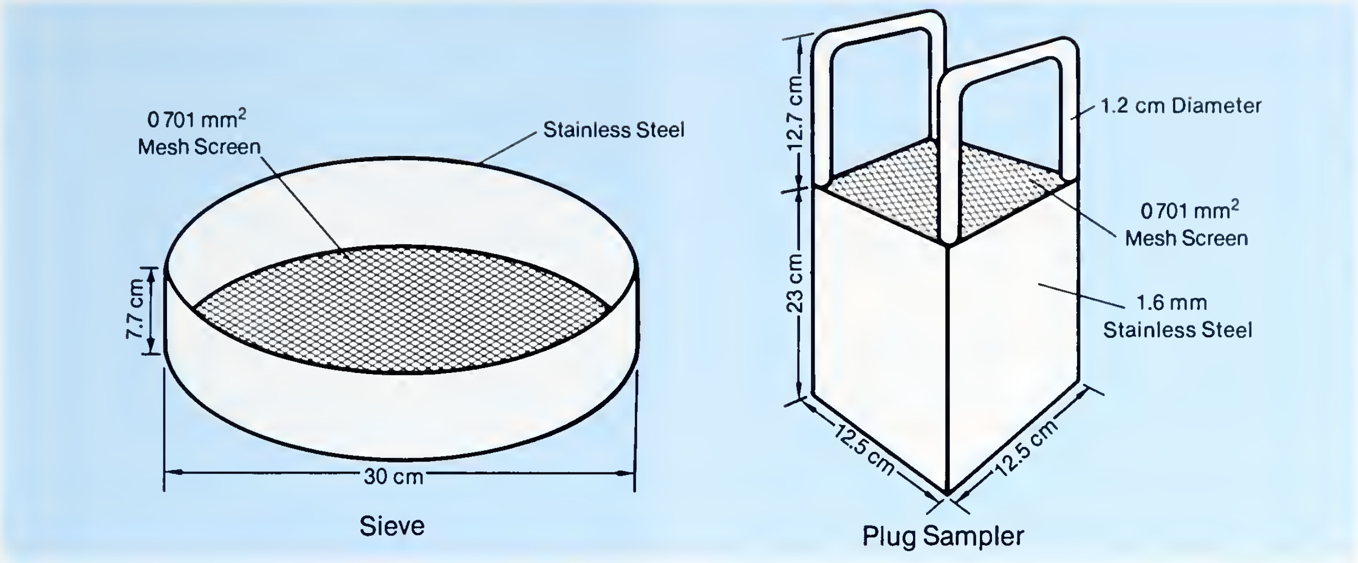


Photo Art Flechsig

Another coring device for obtaining quantitative samples of the infauna is a square stainless steel box with handles and a screen covering one end (Figure 9-11). Its rugged construction allows scientists forcibly to penetrate hard substrates, such as sand or vegetated bottoms, as well as softer sediments. The sampler, currently in use by NOAA/NMFS divers, can obtain a 0.17 square foot (1/64 m^2) sample to a depth of 9.1 inches (23 cm). After the corer is pushed into the substrate to the desired depth, one side of the device is excavated and the device is tilted over, after which the corer and sample are pulled free. To prevent any loss of sample, the diver holds the open end of the corer against his or her body while ascending. The contents are then placed in a sieve of appropriate mesh size (Figure 9-11), washed free of most of the sediments, and the residue containing the organisms is placed in jars of preservative. A red dye (usually Rose Bengal) is added to the preservative to facilitate the sorting and identification process.

A Multiple Disc Sampling Apparatus for collecting epibenthic organisms has been developed by NOAA/

Figure 9-11
Infauna Sampling Box



Source: NOAA (1979)

NMFS divers. Each collecting unit consists of a disk 9.7 inches (24.6 cm) in diameter with a surface area of 0.54 square feet (1/20 m^2). Various kinds of material have been used in the construction of the disks (wood, glass, steel, rubber, cement). Rubber and cement generally are superior substrates for most sessile invertebrates. The disks are wired to a galvanized pipe frame placed on the bottom by divers. Individual disks are removed at intervals by divers who place a canvas collecting bag over the disk and cut the wire holding the disk to the frame. This procedure minimizes the loss of motile organisms. Individual bags containing the disks are filled with a narcotic solution (7.5% magnesium chloride mixed 1:1 with seawater) for 1 hour and the disks are then preserved in a 10 percent formalin solution. Wiring disks rather than bolting them simplifies the operation and eliminates the problem of corroded fastenings. The experimental design—collecting frequency, substrate material to be tested, or other epifaunal survey requirements—dictates the number of disks to be used. Because of the large size of disks, the epifaunal assemblages that are collected by this method are more typical of those found on natural substrates. However, only a portion of each disk is examined and enumerated.

Some knowledge of geological techniques is helpful when sampling. For example, on rocky substrates it is important to know how to measure angles of inclines on overhangs or shelves, because this angle influences the orientation of many organisms (see Section 9.10.1). Similarly, knowing the composition of the rock is important in determining whether or not organisms can bore into it or merely attach to it, and the rock's composition will also determine its resistance to erosion over long periods. In soft bottoms, it is useful to describe sediment grain size and bottom configurations; determinations of grain size, chemical composition, and other physical characteristics are best done by scientists especially equipped to handle these tasks. Situations vary, and it may be helpful to consult geologists for recommendations on where to obtain the appropriate geological data.

9.5.3 Airlift Sampling

An airlift is a sampling device that consists of a long plastic pipe equipped with a device to supply air at the lower end. The airlift carries sediment and organisms to the top of the pipe in a stream of air and water, so that they can then be emptied into a mesh bag of a certain size (see Section 8.9.1). Large areas of soft bottom can be collected in a very short time with this device, and the samples can be screened through the bag in the process. When used with a diver-held scraping device, an airlift is also useful on hard substrates, especially to collect the small organisms that tend to escape when attempts are made to "scrape and grab."

9.5.4 Midwater Sampling

Although plastic bags have been used successfully to sample swarming copepods and small aspirators have been used to sample the protozoan *Noctiluca*, animals in midwater must generally be collected using other techniques. It is difficult to sample even very small animals, such as the copepod *Oithona*, without disturbing them. Although small, copepods swim rapidly for short distances and readily dodge water bottles, nets, or aspirators. If nets must be used, they are deployed most effectively by divers swimming the nets by hand or guiding diver-propulsion units to which the nets are attached (see Figure 9-8). No objects should obstruct the mouth of the net, because even monofilament bridles cause zooplankton to avoid nets.

The diver can easily capture larger, less motile zooplankton that range from several millimeters to a few centimeters in size, such as the gelatinous medusae, ctenophores, salps, pteropods, and chaetognaths, etc., by permitting the animals to swim into a hand-held container, preferably of clear plastic or glass (see Figure 9-12). This is the preferred method of data collection for all aspects of laboratory marine research, because it is the way to collect these delicate animals without the damage that normally occurs even with the most carefully handled net.

Estimating density of planktonic aggregations. For many kinds of organisms, density and distribution can be determined photographically without disturbing the aggregation. The use of an 80-mm lens and extension tubes provides a small measured field of view some 11.8 to 15.7 inches (30 to 40 cm) from the camera. Depth of field varies systematically with f-stop (see Section 8.13). Instructions for some underwater cameras provide these calculations, but investigators can make them for their own cameras by photographing underwater targets at a series of known distances in front of the camera with different f-stops and determining the depth of field in the resulting photographs. Density of organisms such as copepods within swarms is determined by counting all of the animals in focus in the photograph, i.e., within a known volume determined by area of field times depth of field. When the number of organisms in focus is large, density can be estimated by measuring the distance from one individual to its closest in-focus neighbor for each of some 20 individuals within a single plane. These distances are averaged and the density of the aggregation is estimated by entering this average into the formula for close packing of spheres or of isohedronic arrays. Use of the formula

$$1{,}000{,}000 \text{ cm}^3/0.589 \text{ x (average nearest neighbor's distance in cm)}^3 = \text{Number of organisms per meter}^3$$

is preferred because isohedrons pack symmetrically along all three axes, whereas spheres do not.

Figure 9-12
Use of a Hand-Held Container
to Collect Zooplankton

Photo Al Giddings

Density measurements for animals sparsely distributed can be obtained more easily by swimming line transects between tethered buoys while counting the number of animals that pass through a grid of selected size (see Figure 9-13). Divers also may drift slowly on a tether with the ship and estimate densities by measuring the drift rate and counting the number of organisms that pass through a grid in a specified time.

Replicated measurements permit the application of most normal statistical procedures used in quantitative ecology. Some tests are of questionable validity because many statistics depend on presupposed patterns of normal distributions, patterns that may not apply to three-dimensional arrays. Nonetheless, many of the sampling procedures used by the terrestrial ecologist may be applied to underwater sampling. Biological oceanographers now use these new techniques frequently.

9.6 SHELLFISH STUDIES

The use of diving as a research tool to study lobsters, crabs, scallops, and other types of shellfish has increased

Figure 9-13
Use of a Plexiglas Reference Frame for Estimating Population Densities in Midwater

Courtesy ®National Geographic Society
Photo Al Giddings

as a result of both the commercial importance of these living resources and the difficulty of sampling these organisms effectively with conventional surface-oriented equipment. In general, shellfish studies have been directed toward the ecology of these organisms, their behavior in relation to sampling gear, the efficiency of sampling gear, and the potential effects of conventional sampling techniques on the bottom environment and its fauna.

Historically, more underwater studies have been conducted on the American lobster of the New England coast than on any other single species of shellfish. In addition, extensive studies have been done in Florida and California on the spiny lobster (Herrnkind and Engle 1977, Marx and Herrnkind 1985).

Direct in-situ observation of lobsters is the most effective way to study lobster ecology and behavior. Comparative studies of lobsters in the laboratory-aquarium environment have shown that their behavior is altered significantly when they are in captivity. For example, lobsters held in captivity are highly cannibalistic, but cannibalism is rare in the natural environment. In addition, lobsters less than one-half pound (0.22 kg) in size generally are not nocturnally active in their natural environment but are active at night in the confines of an aquarium tank. Lobsters spend most of their first 3 years of life in a labyrinth of tunnels projecting as many as 3 feet (0.9 m) into the boulder-rock substrate of the ocean bottom (see Figure 9-14). Replicating this substrate in an aquarium is difficult.

9.6.1 Collecting Techniques

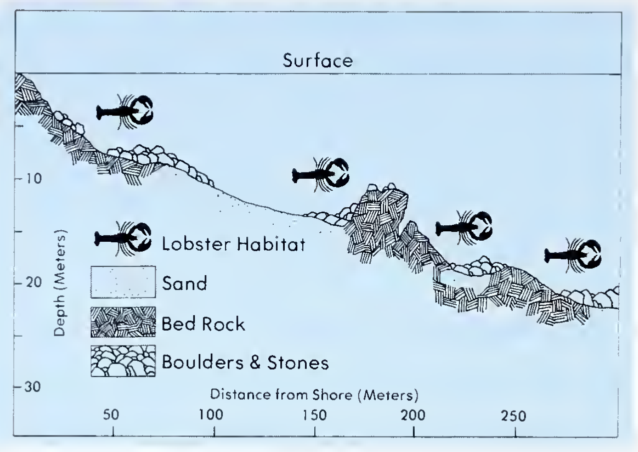
Many shellfish (crabs, lobsters, and clams) inhabit tunnels and burrows on the bottom. Others (scallops, oysters, and abalone) live in beds and reefs or creep across the seafloor and rocks. When collecting shellfish, divers should always wear gloves and carry catch bags.

Lobsters inhabit burrows, tunnels, and caves in shallow coastal waters and in ocean depths that are beyond the range of surface-supplied diving. Those more than one-half pound in size are nocturnal in their movements; during daylight hours, they remain in their homes. When picked up, spiny lobsters and bulldozer lobsters should be held by the back; if grabbed around the abdomen (tail), the tail can cut a diver's fingers. The American lobster can be collected easily by grabbing it from the back, behind the claws. Lobsters can also be grabbed by their ripper claws and held for 1 to 2 seconds; if held longer, their crusher claws will be brought into action. Lobster claws should be inactivated by banding or pegging before the animal is put in a catch bag; this will prevent animals from crushing each other. Lobsters frequently will autotomize (drop) antennae and claws when handled; American lobsters do this especially during the winter months, when water temperatures range between 28.5° and 34.0°F (-1.94° and 1.1°C).

The conventional method for commercial harvesting of the spiny and New England clawed lobster is the wire or wooden trap. Divers should assess the efficiency and design of this gear before using it, bearing in mind that spiny lobsters move much faster than American lobsters and are much more sensitive to being disturbed.

Commercial crabs are found in waters ranging from shallow estuaries to ocean depths that are beyond conventional diving limits. Gloved divers can catch them easily by hand with short-handled scoop nets and tongs. Caution should always be exercised when collecting crabs because they can pinch with their claws; depending on the size and species, such injuries can vary from a cut finger (blue crab or Dungeness crab) to a broken finger (stone crab or Alaskan King crab).

Figure 9-14
Benthic Environment
of the American Lobster



National Marine Fisheries Service

Blue crabs live in the shallow, temperate waters of estuaries, bays, and sounds in the Gulf of Mexico and Atlantic Ocean. When frightened, they will burrow quickly into the bottom or swim away with great speed. These fast swimming, pugnacious crabs can be collected easily with a short-handled scoop net. They can be found partially buried and lying around shells and rocks or walking along the bottom.

Stone crabs inhabit burrows, depressions, and shell houses in the coastal waters along the South Atlantic and Gulf of Mexico states. An 18 inch (45.7 cm) pair of tongs is useful to extricate them from burrows and shell houses. Their claws can be brought into action quickly and can easily crush fingers, so they should be handled carefully. Stone crabs should be handled by their rear legs.

The **Alaskan King crab** lives in the cold waters of the North Pacific Ocean and the Bering and Okhotsk Seas. Young crabs (2 to 3 years old) inhabit shallow waters in large "pods" of 2000 to 3000 individuals and migrate to deeper water as they mature. Mature crabs (males range up to 6.6 feet (2 m) and 22 pounds (10 kg)) migrate seasonally between deep and shallow water to spawn. As the crabs walk across the bottom, divers can collect them by grabbing them cautiously from behind.

Dungeness crabs are found in shallow inshore, estuarine, and offshore waters from southern California to Alaska and the Aleutian Islands; they live in waters that are up to 328 feet (100 m) deep. These large crabs, which range up to 9.4 inches (24 cm) across the back and up to 2.2 pounds (1 kg) in weight, can move quickly, occasionally even faster than a diver can swim. Individual crabs can be captured from behind and placed in a mesh bag, if this is done cautiously.

Oysters inhabit relatively shallow waters in estuaries, bays, and sounds in the Gulf of Mexico, off the Atlantic coast states, and in the North Pacific. They occur individually, in clusters attached to rocks and pilings, and together, in large beds of thousands of individuals. These sedentary shellfish are easy to collect by hand. A pry bar can be used to collect samples that are attached. Oysters can temporarily be piled loosely on the bottom during harvesting.

Scallops live in bays, sounds, and ocean bottoms in depths up to 328 feet (100 m). Density varies from one or two individual scallops to dozens per square meter. They are collected easily by hand or scoop net. Loose piles of scallops should not be left on the bottom because the scallops may swim away. Getting one's fingers stuck in the shell of a live scallop is painful.

Abalone inhabit rocky coasts from Alaska to southern California. They are nocturnal foragers of algae and rest during the day at their "homespots" on a rock. An iron pry bar can be used to pull them loose, and they can sometimes be pried loose quite easily with a quick motion.

9.7 TAGGING AND MARKING TECHNIQUES

Tagging aquatic organisms can provide information on many aspects of underwater life, including coastal migration, nearshore to offshore movement, seasonal distribution, and growth rate. Because tagging can damage the animal, the value of the information gained from a return should be carefully considered.

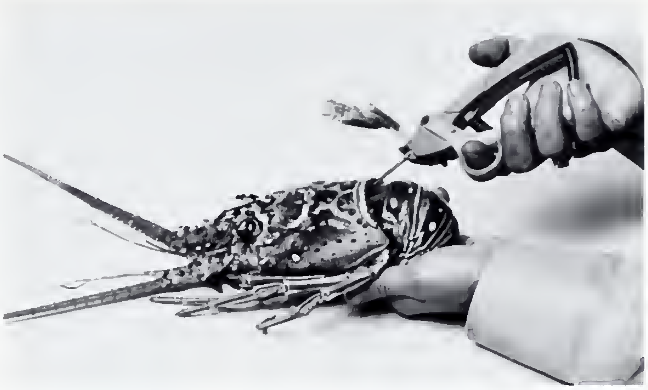
There are two different methods of tagging marine organisms: The animal can either be tagged in situ or be captured and brought to the surface for tagging. Figure 9-15 shows an electroshocking grid used to collect fish for tagging. Although more traumatic for the organism, the latter method has the advantage of allowing the animal to be weighed, measured, and examined in detail before release. Methods are available to take measurements in situ under water. Although body dimensions can be measured under water, a satisfactory method for determining body mass (weight) has not been developed.

Ebert (1964) described a fish-tagging gun that inserted a standard dart tag into bottom-dwelling fishes and which could be adjusted to account for skin or scale thickness. More recently, the plastic "T" tag, originally designed for marking clothing (Figure 9-16), has been used. The needle of the tagging gun is placed against the organism and the tag is inserted into the body tissue. With practice, the depth of tag penetration can be controlled by the tagger. Because this particular gun has many metal parts, it must be washed and oiled carefully to avoid corrosion.

Figure 9-15
Diver With Electroshock Grid

Courtesy Diving Systems International
Photo Steven M. Barsky

Figure 9-16
Tagging a Spiny
Lobster on the Surface



Courtesy Floy Tag and Manufacturing Inc.

Lobsters have been tagged within their natural environments with short-term (lost at shedding) and long-term (retained at shedding) tags and marks. Lobster dens may be marked with styrofoam floats, numbered carefully to note specific locations. Color-coded tags may be inserted into the dorsal musculature between the abdomen and thorax of the lobster with the aid of a No. 20 syringe needle (Figure 9-17). A secondary mark may be made by punching a small hole (0.16 in. or 4 mm) into one of the five tail fan sections; this mark will be retained through at least one molt and will permit recognition of a lobster that has lost its primary tag. Movements and locations of lobsters at night may be determined by using small sonic tags (pingers). These tags are small (about 1.2 x 2.0 x 0.4 in. or 3 x 5 x 1 cm) and weigh only a few grams. Several types are available commercially. They operate in the general frequency range of 70 kHz and may be picked up as far away as 1200 feet (363 m) on an open bottom and 60 feet (18.4 m) when the tagged lobster is in a crevice.

When conducting a survey of lobsters, it should be kept in mind that the very presence of the diver and the tagging procedures may affect overall behavior. In one study, a significant alteration of the population distribution was noted during the course of several weeks of capturing and tagging (Miller et al. 1971).

Long-term and short-term tags also have been used by divers in **crab** population studies. Long-term dart and spaghetti tags can be inserted at the isthmus of the carapace and abdomen, the point from which the crab exits when shedding. Short-term tags can be applied to the legs or carapace. Carapace tags for blue crabs consist of an information-bearing plastic spaghetti tag with a loop of stainless leader wire at each end. A loop is put around each of the lateral spines of the carapace, adjusted, and then crimped with a leader sleeve. Other methods of short-term tagging include staining by injection or dipping with vital stains, fluorescent dyes, or phosphorescent dyes.

Tagging of **oysters**, **scallops**, and **abalone** can be accomplished by attaching Petersen tags with glue or a wire, painting the shell, using colored quick-setting cement, or staining the shell with vital stains. The excurrent holes on abalone shells are very convenient points of attachment for tags. A method for tagging **abalone** has been reported by Tutschulte (1968). This technique involves attaching a small battery-powered luminous beacon to the shell. During the night, the movements of the abalone with the light source on its shell are recorded on sensitive film by a camera fixed several meters above the seafloor. Movement of a marked animal may be recorded either as light streaks (in time exposures taken with a still camera) or as a moving point of light (in time-lapse cinematography). Animals studied by this method are subjected to a constant, low-intensity light and are not illuminated by the periodic flashes of high-intensity light required for direct observation in night diving; behavioral changes caused by unnatural light flashes are therefore probably eliminated with this method.

A technique has been developed for tagging **echinoderms** (Lees 1968). This method involves drilling a tiny hole completely through the sea urchin and inserting an inert filament (monofilament line or high-quality stainless steel line) that has been strung with small pieces of color-coded vinyl tubing. The urchin first is carefully removed from its hole or crevice and placed in a holding device made from a weighted plastic bowl lined with thick polyurethane foam; this enables the diver to press the urchin down into the foam to hold it still during the drilling operation. An ordinary hand drill fitted with an 18-gauge, 4 1/2-inch-long (11.4 cm) hypodermic needle is used to drill completely

Figure 9-17
Tagging a Spiny Lobster in Situ

Source: NOAA (1979)

through the test and body cavity. After the filament or wire has been threaded through the needle, the entire drill/needle assembly is slowly withdrawn, pulling the wire through the body cavity and leaving wire and tags in place on the urchin. The ends of the wire are then twisted together to form a loop, and the loose ends are trimmed.

The same technique can be used to tag **sea cucumbers**, except that the wire can be pushed through by hand instead of with a drill. Animals tagged in this fashion seem to be unaffected, and tags have been known to last for 6 to 8 months. With sea cucumbers, trimming the tags short is important because fish may otherwise nibble on the long loose ends.

Tagging **finfish** requires special skill and handling. The size of the fish must be sufficient so that the tag will not impair the ability of the fish to navigate, forage, or avoid predators. Lake (1983) lists several guidelines for tagging finfish:

- use barbless hooks to catch the fish
- avoid the use of bait
- don't tag fish that have been tired by a long fight
- hold fish with a wet rag over their heads
- keep gills free of sand and dirt
- don't tag fish that are bleeding from the gills
- tag during cold water season whenever possible
- during tagging, make sure that fish are not out of the water for more than 60 seconds.

A number of techniques have been used to tag finfish. Three common methods involve Petersen disk tags, spaghetti tags, and dart tags. Disk tags are about 3/8 or 1/2 inch (0.95 to 1.27 cm) in diameter and come in a variety of colors. They can be attached to the back of the fish with monofilament line. This type of tag should not be used on fish that will grow to a large size because the tag will cause pressure on the fish as it grows (Randall 1961). Spaghetti tags are made of soft tubular vinyl plastic about 1/16 inch (0.16 cm) in diameter, with monofilament nylon in the center. This type of tag can be attached by running the line through the fish's back beneath the rear of the dorsal fin. Because this type of tag can snag on rocks or coral, the method is not recommended for reef fishes. Dart tags consist of a vinyl plastic tube with a nylon tip and barb. They can be inserted into the back of the fish with a hollow needle so that the plastic streamer bearing the legend trails posteriorly, with a slight upward tilt. Although this technique permits fairly rapid tagging, these tags tend to come loose more easily than those implanted via the first two methods.

Another method of tagging finfish involves injecting colored dyes subcutaneously (Thresher and Gronell 1978). This technique has been used successfully in situ for studying the behavior of reef fish. The dye can be injected via disposable plastic syringes and disposable needles. Although several different dyes have been used, plastic-based acrylic paints are the most satisfactory and apparently do not harm the fish or significantly affect their behavior. Two methods have been used, depending on the size of the species to be tagged. For small-scaled and scaleless species, the needle is inserted from the rear, parallel to the body surface, so that the tip enters the skin, runs underneath it for a short distance, and then emerges. This in-and-out technique ensures that the tag is placed immediately below the skin, the best position for producing a long-lasting tag. Slight pressure should be placed on the syringe to start the flow of dye (and ensure that the needle is not plugged), and then the needle should be pulled back under the skin and withdrawn. The smooth motion results in an even line of color below the skin. For large-scaled species, the needle should be inserted under the rear edge of a scale and moved gently from side to side while pressure is applied to the syringe, which causes a small pocket of dye to be deposited under the scale. Acrylic paint tags inserted in this manner have lasted as long as 16 months; durability depends in part on the color of the paint.

Scallops have been marked successfully using a quick-setting calcium carbonate cement (Hudson 1972). This material meets four criteria: 1) it does not harm living tissue; 2) it is easy to apply and readily visible; 3) it adheres to a wet surface and hardens under water; and 4) it makes a durable mark. The recommended mixture for this purpose is:

- seven parts Portland gray (or white) cement (Portland Type II is best because it is formulated especially for use in seawater)

- one part moulding paste
- two parts builder's sand (fine grain).

This mixture will start to harden in 3 to 5 minutes (or sooner if less moulding paste is used). The materials should be thoroughly mixed while dry, and three parts of water should be added to 10 parts of dry mix. If colored cement is desired, no more than 10 percent additive by volume should be used, so that the strength of the cement is not reduced. The final consistency should be similar to that of a firm putty.

To apply cement to a scallop, the organism should be removed from the water and the upper valve should be pressed into a soft sponge to remove excess water. A small quantity of cement (about 1/2 cc for scallops 0.4 to 0.8 inch (10 to 20 mm) in shell height and 1 cc for scallops 1.2 inch (3 cm) or larger) is placed near the lip and then rubbed firmly across the shell at right angles to the ribs. This tightly grouts the depression between the ribs and leaves a thin coating of cement over the shell. Several quick thumb strokes are necessary to distribute cement evenly out to the lip so that new shell growth can be measured accurately. Only enough cement should be applied to fill the inter-rib areas; the upper surface of the ribs should be visible through the coating. Marked scallops can be returned immediately to the holding tank, where they should be held for several hours to allow further hardening. Scallops marked in this way have retained this marking material for 15 months or more.

The same type of cement has been used to transplant live coral in reef areas and to mark large marine gastropods and other delicate bivalve molluscs (Hudson 1978). Figure 9-18 shows a living elkhorn coral, *Acropora palmata*, implanted on a rocky outcrop. Another method for marking marine organisms involves the use of various dyes. Alizarian Red dye has increasingly been found useful for making permanent growth line marks in living corals and other invertebrates. The dye does not harm the coral, and subsequent growth can be measured after the coral is sliced with a saw.

Figure 9-18
Elkhorn Coral
Implanted on Rocky Outcrop

Photo J. Harold Hudson

9.8 BOTANICAL SAMPLING

Studies of benthic macroalgae and seagrasses in their natural environments focus on both nearshore intertidal zones and depths. This is the region where sufficient light can penetrate the water to support the growth of diverse and often dense associations of photosynthetic organisms that grow attached to bottom substrates (Figure 9-19). Benthic algae can occur at depths greater than 656 feet (200 m), but few species occur in these relatively deep habitats. The sites where most research involving algal and angiosperm vegetation takes place are shallow enough to be accessible with scuba equipment.

Wherever stable substrates occur nearshore, on rocky beaches, in estuaries or bays, or on coral reefs, various forms of plants will develop. As with all underwater work, however, site-specific features limit and strongly influence the choice of sampling method. Large-scale biologic studies may include samples or catalogues of plants, recorded with estimates of area covered. Data may sometimes be combined for forms or species (crusts, *Iridaea* spp., for example), depending on the need for taxonomic precision. Large discrete thalli, such as taxa of brown kelp, usually are counted. In some cases only indicator taxa, selected on the basis of economic value, dominance, or ease of identification or counting, are of interest. Sampling programs that are designed to record abundance and distribution patterns of plants and other sessile organisms are described in Sections 9.5.1 and 9.5.2.

Presence/absence data or estimates of abundance are utilized for experimental studies as well as for descriptive investigations. The methods employed for these various objectives rely on sampling procedures that have largely been adapted from terrestrial or intertidal studies. Their applicability to subtidal work depends on their efficiency under conditions where time, mobility, and visibility are often severely limited. These factors must be assessed independently for every situation.

Figure 9-19
Algal Cover
of Rock Substrate

Photo Bill Bunton

9.8.1 Field Procedures

As with any ecological project, the objectives and constraints of the study and the features of underwater sites determine which techniques are appropriate. In recent years, subtidal biological methods have been summarized in books that draw on hundreds of scientific and technical publications. These sources provide up-to-date reviews of methods, as well as discussions of their relative advantages and disadvantages. Accordingly, the following paragraphs represent only a brief review of botanical field procedures.

Generally, underwater botanical sampling, whether of data or specimens, depends on the use of transect lines, grids, and quadrats arranged in fixed, systematic, or haphazard ("random" is rarely practical) positions. Recently, circular sampling designs have been found useful in sites of heavy surge, rough water, or low visibility. In circular sampling, a radius-length line attached to a central fixture is used to partition the area and guide the diver. Underwater sites are usually located on the surface by sighting or buoys and on the bottom by a variety of fixed markers. Data can be recorded by notations on data sheets treated for underwater use, by collections of organisms, photography, voice recorder, or television camera (see Section 9.3).

Methods suitable for sessile animals are particularly appropriate for investigating marine plants. Studies that rely on these methods seek, in general, to differentiate and classify plant communities and to analyze the data to identify changes. As an index of productivity, standing crop data can be obtained by collecting the entire vegetation from a given area and sorting the material into component species in the laboratory. These specimens can then be dried, weighed, and reduced to ash for analysis of organic content.

For ecological studies or census data, the size and number of quadrats to be used must be determined by appropriate tests, such as species accumulation curves, and researchers often find it advisable to use an area somewhat larger than the minimal one to be confident of establishing statistically significant differences between samples.

Seasonal variations in the diversity and abundance of plants is very conspicuous in certain parts of the world. To get complete coverage of events in an area and to gain understanding of the natural cycles, it is necessary to sample repeatedly throughout the year. It is best to return to the same station to monitor changes over time.

Some plants have a narrow temperature tolerance, and these may act as indicator species because their presence or absence suggests certain environmental characteristics. North latitude kelp taxa, for example, do not live in warm water and are not found in tropical latitudes except where cold currents or deep cold water provide suitable circumstances.

9.8.2 Collecting Techniques

Before beginning a study that requires the collection of plants, an investigator should survey local environmental conditions so that he or she will know where and how to sample. Most macroalgae require a hard substrate for attachment, and the diversity of plants on rock surfaces usually is far greater than in soft sediment or sandy areas. Pilings, shells, dead corals, barnacles, shipwrecks, and mangrove roots are other places algae are likely to attach. Marine vascular plants (seagrasses) follow the reverse pattern; most species grow on soft or sandy substrates, although some, such as *Phyllospadix*, grow on the rocky shores of the western United States. Frequently, seagrasses and larger algae themselves provide substrates for a great array of smaller epiphytic plants.

Because benthic plants are attached to the substrate, a tool such as a putty knife, scraper, or knife is usually needed to remove entire plants if these are required for voucher specimens or for later study. Mesh bags or small plastic vials with attached lids are useful for holding samples. If plant samples are necessary for identification, portions or selected branches are often adequate. If there is no reason for collecting material, a non-destructive sampling or experimental design can be implemented. If small thalli are needed for laboratory examination, it is often more efficient to collect pieces of rock or substrates than to remove and handle plants during the dive.

When several divers are involved in a study, a system for incorporating "unknowns" (specimens that cannot be identified in the field) should be included in the planning stage. Vouchers for such data as well as for all critical taxa should be assembled and retained with the raw data.

If an investigator wishes to obtain a census of an area, collections from diverse substrates should be sampled. Because some plants live only in intertidal or shallow water, while others live only in deep water, collections should be made over a broad depth range. Data for large plants, such as the kelp *Macrocystis* (Figure 9-20), that may be 100 feet (30 m) in length, with holdfasts 3 feet (0.9 m) in diameter and as many as 400 or 500 stipes, are usually based on in-situ observations and measurements. Care should be exercised when placing several types of marine plants in a common container, because plants that have extremely high acidic content may damage other forms of algae in the container.

A clipboard with waterproof paper and pencil for notes and a field notebook should be used to record data immediately after diving. Diving observations should be recorded as soon as possible. Ideally, field data should include notes on depth, substrate, terrain, water temperature, current, visibility (clarity), conspicuous sessile animals, herbivores, the date, time, methods used, and the collecting party. If possible, information on available light, salinity, and other environmental factors should be obtained. Census data become more useful if the relative abundance of each species is at least estimated, i.e., whether common, occasional, or rare. Many marine species are inconspicuous, and these require careful microscopic examination and identification in follow-up work.

Accurate light measurements within a given plant community can be obtained by using small, self-contained light meters. The use of photographic light meters that incorporate selenium photocells is unsatisfactory unless restricted spectral regions, isolated with colored filters, are measured. This is because a sensing system that responds differently to different wavelengths is being used to measure light that is becoming increasingly monochromatic with depth. The introduction of colored filters in front of the meter greatly reduces its sensitivity. An opal cosine collector can be added to make the system behave more like the plant's surface does in terms of light absorption, but such collectors can only be used in shallow, brightly lit waters. The apparatus needed to make such measurements generally incorporates a selenium photocell of increased surface area, which augments the current output per unit of illumination; a system for easily changing the colored filters; and a sensitive ammeter whose range can be altered by current attenuation circuitry.

Figure 9-20
Diver in Giant Brown Kelp (Macrocystis) Bed

Source: NOAA (1979)

9.8.3 Specimen Preparation and Preservation

To determine the kinds of plants present, notes should be made on the collected specimens while they are still fresh. Herbarium and voucher specimens can be made from either fresh or preserved material. Plants prepared soon after collection tend to retain their natural color better than those that have been preserved, because alcohol bleaches thalli more than formalin does.

Although procedures for drying and mounting large algal and seagrass specimens are described in many easily obtained and standard guides, a few simple procedures are described here. Most marine algae have a gluelike substance on the outside of the cells that makes specimens more or less self-adherent to most kinds of paper. Standard herbarium paper will preserve a collection permanently, but this paper is not a prerequisite for making a useful set of voucher specimens. Formalin (2.5-5%) will preserve small or delicate forms, and permanent slides are useful for ongoing work. Time and place of collection and the name of the study or collector should be associated with every specimen by label, with a numbered reference to a field book or data set.

There are standard herbarium methods for pressing plants and some special variations for marine algae. The usual approach is to float specimens in large, flat trays and to slide them carefully onto sheets of heavyweight herbarium paper. Using water, the plants are arranged on the paper; the paper is placed on a sheet of blotting paper and topped with a square of muslin or other plain cloth or a piece of waxed paper. This is covered with another blotter, and a corrugated cardboard "ventilator" is placed on top. Another layer of blotter—paper—plant—cloth—blotter—cardboard is stacked on top. When 20 or 30 layers have been stacked, the pile should be compressed, using a weight or the pressure from heavy rocks or from straps wrapped around the plant press. The top and bottom pieces should be stiff; boards slightly larger than the herbarium paper and blotters are generally used. After several hours (or overnight), the stack should be taken apart, and the damp blotters should be replaced with dry ones. Many small algae dry in one day using this technique, but some, such as the large brown algae, may take a full week to dry completely, depending on air humidity.

The usual method for preserving specimens for later detailed examination and herbarium preparation is simple and effective. For each station, one or more large plastic bags can be used to hold samples of larger plants. Small bags or vials should be used for selected fragile or rare plants. The best general preservative is a solution of 3 to 4 percent formalin in seawater buffered with 3 to 4 tablespoons of borax per gallon. Ethyl alcohol (70%, made up with fresh water) is recommended for longer storage. Plant and animal specimens should not be mixed.

Permanent slides may be made of microscopic species. One common method uses a solution of 80 percent clear corn syrup and 4 percent formalin. The slides should be allowed to dry slowly; as the syrup dries, more should be added. The edges of the slide can be sealed with clear nail polish.

Plants collected for histological study should be preserved in a manner that is appropriate for the particular technique to be used. In all cases, preserved specimens should be kept in a dark place, because exposure to light causes preserved plants to fade. Samples obtained from many stations can be kept in separate bags in a single large storage drum that can be sealed tightly to prevent formalin from leaking out. For shipping, most of the preservative can be drained off, because the plants, once preserved, remain in good condition for several weeks if they are kept damp.

An alternative method for preserving whole large plants involves soaking them for several hours or days in a solution consisting of 10 percent carbolic acid and 30 percent each of water, alcohol, and glycerin. Specimens thus preserved may be dried and then rolled up for storage. The glycerin helps to keep the plants flexible indefinitely. Another technique involves partially air-drying giant kelp on newspaper (in the shade) and rolling the plants, beginning with the holdfast. Rolls are tied, labeled, wrapped in paper, and left to finish drying. Specimens so prepared can later be resoaked for examination.

If possible, one wet preserved specimen should be kept for each pressed specimen. This is especially important for unidentified species, because taxonomic classification often depends on cell structure. Some small plants can be preserved with general collections, but delicate specimens should be isolated. Retaining small pieces of rock with encrusting algae attached helps keep the plants intact. Coralline algae and rock-encrusting species require special attention. Articulated corallines may be pressed on paper and then brushed with a diluted solution of white glue as an alternative to older methods of storing in boxes.

Plants collected for particular purposes (electron microscopic study, chemical analyses, culture inocula) require special treatment. It is important to fix or preserve such specimens as soon as they are removed from seawater. Because algae are photosynthetic organisms and the deleterious effects of surface light on the pigment systems of specimens from subtidal habitats can affect other metabolic processes, they should be kept relatively cool and dark until placed in a killing (fixing) solution or used for physiological work.

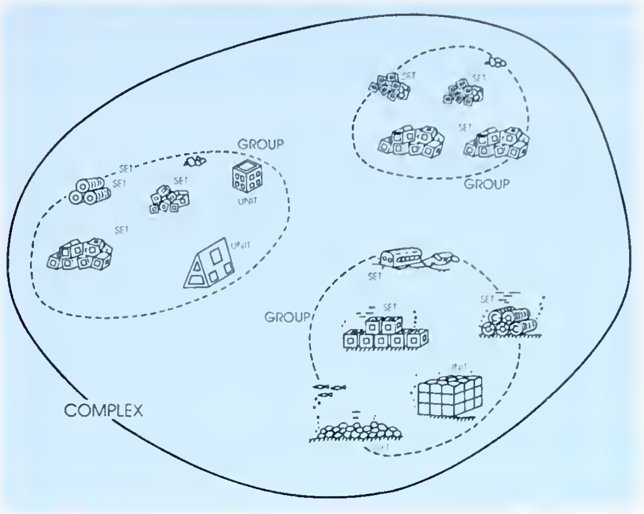
9.9 ARTIFICIAL REEFS

Artificial reefs are manmade or natural objects intentionally placed in selected areas of marine, estuarine, or freshwater environments to provide or improve fish habitats. Much of the ocean, estuarine, and freshwater environment has a relatively barren, featureless bottom that does not provide the habitat that reef fish need. Natural reefs and rock outcrops are limited; less than 10 percent of the continental shelf can be classified as reef habitat. Even if rough bottom consists of

Figure 9-21
Fish Using Tires
as Habitat

Photo Dick Stone, National Marine Fisheries Service

Figure 9-22
An Artificial Reef Complex



Source: Grove and Sonu (1985)

low-profile rock outcrops, it can provide a habitat for fish and invertebrates.

Properly sited and constructed artificial reefs can provide the same benefits as natural reefs. They can enhance fish habitat, provide more accessible and high-quality fishing grounds, benefit the anglers and economies of shore communities, and increase the total number of fish within a given area. Artificial reefs function in the same manner as natural reefs. They provide food, shelter, spawning and nursery habitat, and orientation in an otherwise relatively featureless environment.

Many non-toxic solid wastes or surplus materials have been used in the United States to build reefs—junked automobiles and streetcars, scrap tires (Figure 9-21), damaged concrete pipe and building rubble, surplus or derelict ships, and numerous other materials, including gas and oil structures. Rocks, tires, Christmas trees, and brush piles have been popular reef materials in fresh water. More recently, fabricated structures such as Japanese-style fish houses, concrete structures, and fiberglass-coated plastic units have been tested in the United States. Figure 9-22 shows an artificial reef complex. Fabricated units are commonly used in Japan and Taiwan. Fish aggregating devices (FAD's) also are becoming popular in the United States; these have been used for many years in the western Pacific.

Although artificial reefs can enhance recreational and commercial fishing opportunities, creating a successful reef involves more than placing miscellaneous materials in ocean, estuarine, and freshwater environments. Planning is needed to ensure the success of artificial reefs. If materials are improperly placed or constructed, all or part of a reef can disappear or break apart and interfere with commercial fishing operations or damage natural reefs in the vicinity.

Divers can play a key role in documenting the success of an artificial reef. The charting of reef material on the site and any changes that occur over time are important pieces of information to researchers and managers. Also, diver estimates of reef fish populations can be made by direct counts of the number and species at the reef sites. Species, number of individuals, mean lengths, and behavioral observations should be recorded on waterproof data sheets (see Section 9.3). When visibility is 4 feet (1.2 m) or more, these observations can be made by two or more divers. Each observer makes counts by species for sections of the reef, and these are then totaled for the entire reef. The totals obtained by all observers are averaged for a mean species count of territorial and schooling fish, such as black sea bass, Atlantic spadefish, snappers, grunts, and most porgies. For seclusive fish, such as cardinalfish, morays, and certain groupers, the highest count obtained by any one observer is used. Although the accuracy of fish population estimates varies with visibility, species, and time of day, it is assumed that, if conditions remain constant, the counts represent population density. Photographs taken at intervals from the same location also can be used to count and identify species. In this case, the photo print should be placed on a soft surface and a pin hole put through each identified fish; the print should then be turned over and the holes counted. Visibility should be measured after taking the picture to compare the areas covered by different photographs.

Diver-biologists have used direct observation techniques to demonstrate that artificial reefs can be used to augment productive natural reef and rough bottom areas. They have also shown that these structures increase total biomass within a given area without detracting from biomass potential in other areas.

9.10 GEOLOGY

Diving is an invaluable tool for many aspects of geologic research. The advent of scuba in the late forties and early fifties permitted easy access to the shallow subaqueous environment for the first time. The results of in-situ underwater studies soon began to appear in the literature. Since that beginning, the scientific applications of diving have increased to the extent that many geologists now routinely use scuba as a research tool. Although most underwater geologic research has taken place in shallow marine waters, the same techniques generally are applicable to research in lakes and rivers.

The topics in this section are grouped into two general categories—characterization and experimentation. Geological characterization includes mapping, sampling, and testing parts of the underwater environment, while experimentation deals with the real-time analysis of specific geologic processes. Experimental geological studies rely in part on information obtained from characterization studies, but they go much further in that they require extensive interplay between geology and other disciplines such as biology or fluid mechanics. Initially, underwater geologic research primarily involved the characterization of existing conditions, but such studies now routinely entail experimentation as well.

Although sophisticated methods have greatly expanded scientists' sampling abilities, careful observation is still the mainstay of most underwater geological studies. In some projects, observations may constitute the main data collected; in other cases, careful documentation may be important either to select sampling sites later or to place a chosen study site into the larger context of its surrounding environment. One of the most important elements of underwater geological research, therefore, is accurate note-taking, coupled with agreement on what was seen. It is advisable to supplement notes with a debriefing immediately after the dive and to record debriefing results along with the underwater notes.

Although most research projects require specific equipment, there are some basic tools that a diving geologist should carry routinely. These include a compass, inclinometer, depth gauge, noteboard, ruler, and collecting bag. These are small items, and many of them can be combined into a single tool. For example, a small, oil-filled plastic surveying compass with inclinometer can be cemented to a clipboard or to a plastic writing surface and a pencil can be attached with rubber tubing; a plastic ruler can also be mounted on the edge of the board (Figure 9-23). Other useful equipment of a general nature might include: a still, movie, or video camera; an assortment of small sampling bags or vials; lights; and small coring tubes.

9.10.1 Mapping

Three basic types of mapping can be accomplished under water: bathymetric, surficial, and geologic. Bathymetric maps display the depth contour of the seafloor. Surficial maps show the two-dimensional character and distribution of the material that comprises the seafloor, and geologic mapping projects a three-dimensional analysis of the rocks that crop out on the seafloor.

Bathymetric mapping is best done from a surface craft with echo sounding equipment. Multibeam swath sonar systems are available in hull-mounted and towed fish configurations; although expensive, their accuracy is unsurpassed. A diver under water generally cannot match the range and efficiency, the accuracy of location, or the precision of depth determination and recording possible from a surface craft. However, in unnavigable water, or when taking precise measurements of a highly irregular bottom or of features too small to be resolved from the surface, underwater mapping may be the only practical means of compiling the bathymetry.

Bathymetric mapping can also be done in detail over a small bottom area to determine the area's microrelief. Small-scale bed forms are an example of an important geologic feature too small to be resolved from surface craft. These forms develop in response to near-bottom currents, and their presence indicates aspects of the dynamics of the environment that otherwise may not be readily apparent. Moreover, such features may be preserved in the geologic record, where they are of considerable use in deciphering ancient environments. Scaled photographs of bed forms provide important information on shape and orientation. In mapping features such as sand ripples, however, the geologist needs to determine the average size of the bed forms over a section of seafloor. The small size of the bed forms, the nature of the sediment, and the fact that bed forms often are located in areas of strong wave-induced or unidirectional currents create difficult sampling problems.

Peterson's Wheel-Meter Tape Triangulation Method. This triangulation method requires a wheel that is mounted on a vertical shaft and that has a rim marked

Figure 9-23
Underwater Geological Compass

Photo Robert Dill

in degrees. The shaft is driven into the bottom at selected locations. The 0-degree mark on the rim is aligned with magnetic north. A meter tape, pulled out from the top of the shaft, measures the distance to any point, with the direction read on the wheel rim where it is crossed by the tape. A slightly larger wheel, mounted over and perpendicular to the first so that it can pivot around it, allows elevations to be calculated from simultaneous readings of upward or downward angles. This is a simple method of making measurements under limited visibility conditions, using two divers equipped with voice communication.

Meter Tape Triangulation Method. This triangulation method is preferable to Peterson's wheel method when small areas need to be surveyed under conditions of reasonable visibility. Although this method is time consuming, it is inexpensive, requires little equipment and only a few divers, and is especially adaptable to level and uncomplicated sites. Control points at known distances from each other are selected and marked on the seafloor around the site. Horizontal measurements with a meter tape made from two of these control points to any object or point on the site provide the necessary information for plotting the position on a plane.

Plane Table Triangulation Method. This triangulation method may be used in clear water or on land, both for position triangulation and for taking elevations. Simple plane tables are necessary. They consist of a wooden table, three movable legs, and a weight. A simple alidade is constructed by combining a sighting device, a tube with cross hairs at each end, and a straightedge on a weighted base. Sheets of frosted plastic are then tacked to the table tops and the alidades are set on these. Two plane tables are placed on the bottom, one on each side of the site, and leveled. Initial sightings are made on a previously selected reference or primary fixed control point and across the site from one table to the other. Lines are inscribed on each plastic drawing surface with ordinary lead pencils and are then labeled. The resultant vectors, plus a measurement of the distance between the two points, establish the position of both tables on a horizontal plane. If the tables are not at the same elevation, the relationship is determined by placing a 19.7 foot (6 m) long calibrated range pole, weighted at the lower end and buoyed at the top with a float, on the lower table. A sighting is made from the upper plane, and the distance between the sighted point on the length of the pole and the lower table provides the vertical elevation relationship.

A diver mans each of the two plane tables. A third diver moves the range pole from point to point on the site, and sightings are taken from each table and labeled consecutively. Elevations are measured by the third diver, who moves a marker up or down the pole until he or she receives a stop signal from the diver manning one of the plane tables. The distance is then measured from that point to the object being positioned. The plane table diver uses the horizontal element of the cross hairs for this measurement. The efficiency of this method is limited by the clarity of the water and the requirement that three divers record each point.

Dumas Measuring Frame Method. This method of precision mapping for small areas has been successfully used by archeologists. A 16.4 foot (5 m) square metal frame is fitted with four telescopic legs and extension couplings. The telescopic legs enable the frame to be leveled a few meters above a sloping site, and the extension couplings allow the size to be indefinitely doubled by fitting new sections into place. Using two sides of the frame as tracks, a horizontal crossbar mounted on wheels can be moved from one side of the frame to the other. This crossbar, in turn, is traversed by a yoke holding a vertical pole. The mobile crossbar, the vertical pole, and the frame are calibrated in centimeters. The vertical pole is adjusted to touch any object within the frame.

The coordinates of the point are recorded from three measurements read on the frame, the beam, and the elevation pole. The details around the point must be drawn by a diver hovering over portable 6.6 foot (2 m) grids placed directly on the site materials. These simple grids are divided into 7.9 inch (20 cm) squares, which are designated by numbers and letters marked on the sides of the grids. The measuring frame is used to fix the positions of the corners of the grid. Although this method and the Dumas Measuring Frame method are no longer used extensively, they may be useful in certain circumstances.

Merifield-Rosencrantz Method. A simple method of determining the three-dimensional positions of a number of ground control reference marker stakes has been developed and tested by Merifield and Rosencrantz (1966). Two divers are used for the survey. The procedure consists of the following operations:

1. A rough sketch of the approximate locations of the points to be surveyed is drawn on a frosted plastic sheet for underwater recording. Using a tape measure, the slant distance between the various points is determined. A lattice work of measurements should be made, forming a triangular net (three sides of all triangles); this eliminates the need for making angle measurements. When possible, more than the minimum set of measurements should be taken. For example, if surveying a square that has a point at each corner, all four sides and both diagonals should be measured. One of these measurements is redundant, but it will enable the divers to check the accuracy of the measurements and to detect errors. (Errors can easily happen when a large number of points is being measured.)

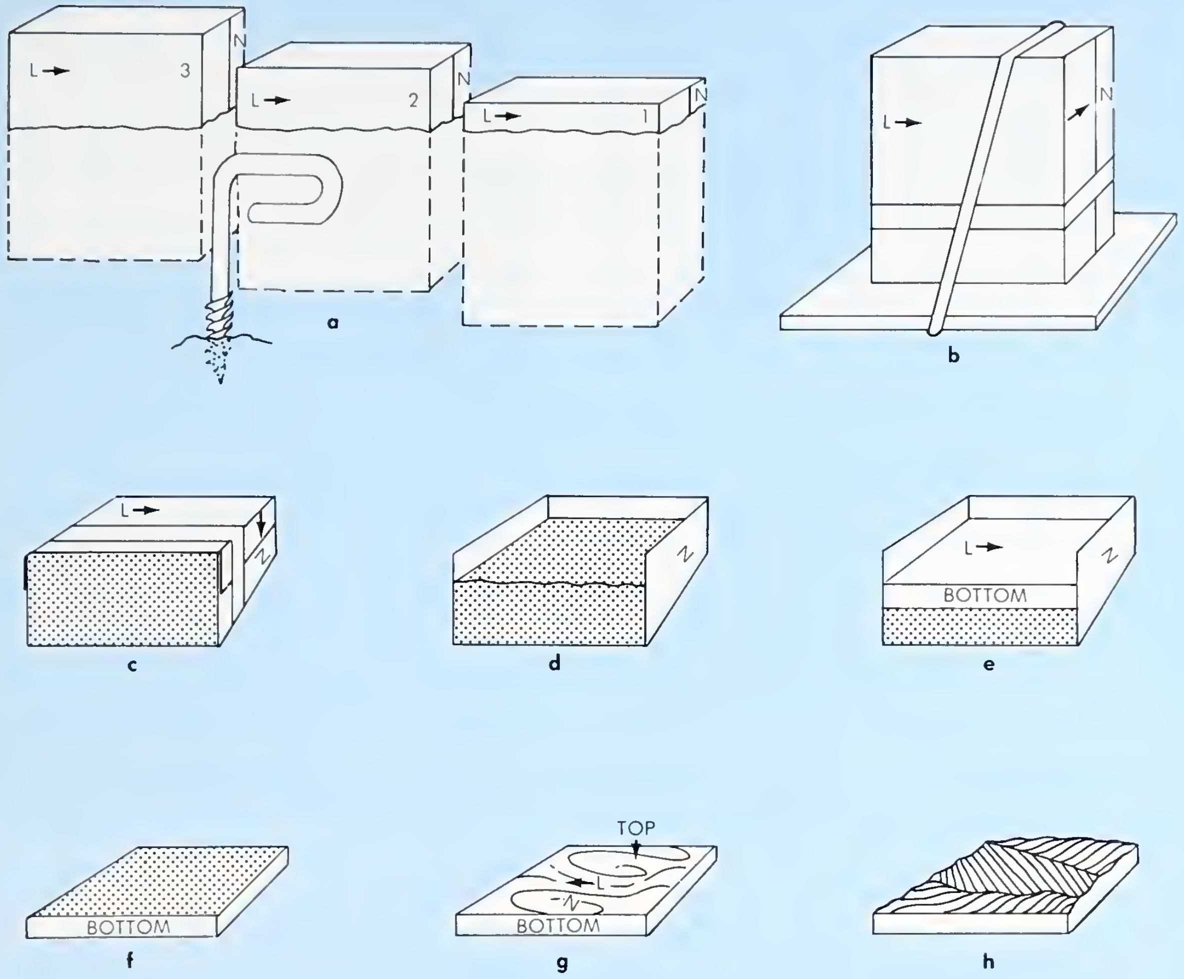
2. The vertical height of each point is measured using a simple but extremely accurate level. A stake is driven into the ground in the middle of the array of points. A clear plastic hose with an inner diameter of 0.37 inch (0.95 cm) is fastened to the top of the central stake, with one end of the hose pointing down. The hose should be long enough to reach the farthest point to be measured. To set up the level, a diver first works all the air bubbles out of the hose. The free end is held at the same level as the end attached to the stake. The diver then blows into the free end and fills the hose with air. As it fills, the hose will rise and form an inverted "u" in the water. The diver then swims to each point to be surveyed with the free end of the hose. A measuring stick is placed on the point and held vertically. The free end of the hose is placed alongside the stick and pulled down until bubbles are seen rising from the fixed end of the hose. When this occurs, the water level at the measuring stick is even with the mouth of the fixed end, and the vertical measurements can be read off the stick. If visibility conditions prevent seeing the fixed end, the hose at the free end should be pulled down slowly until the water level remains steady with respect to the measuring stick. When this occurs, bubbles will come out of the free end, even if poor visibility keeps them from being seen.

3. True horizontal survey distances and vertical heights are then calculated from these data using basic trigonometry and a hand-held scientific calculator. The microrelief of a small section of seafloor covered by unconsolidated sediment can be measured from one or a set of adjoining box cores (the basic box coring technique is shown in Figure 9-24). Because the surficial sediment in the box core may be modified during the coring process, additional steps must be taken when surface relief is desired. Newton (1968) covered the sediment surface with a layer of dyed sand followed by a layer of native sand to provide a protective covering before coring. After the core was impregnated with casting resin, the microrelief was obtained from slabs. This type of box coring is not only time consuming but is also extremely difficult to accomplish under the influence of strong currents.

Ripple height and wave length can be established under water and, where closely spaced, the resulting profiles can be used to create a three-dimensional map of a section of the seafloor. The sophistication of the equipment used to establish ripple profiles differs greatly, and the corresponding resolution of the data varies accordingly. Inman (1957) used a greased "comb" (Figure 9-25) to obtain a profile of the large ripples that form in medium and coarse sand. In principle, this technique should give a fairly accurate profile of the ripples as long as the spacing of the comb elements is small compared with the ripple wave length. In practice, the comb is awkward to use because it has to be handled carefully to prevent grease from fouling divers and equipment and to ensure that the adhered grains are not lost before the trace can be measured. If visibility permits, photographing a scaled rod laid transverse to the ripples produces a quick but accurate measure of ripple wave length (Figure 9-26). To measure the small ripples that form in fine sand, Inman (1957) laid a Plexiglas® sheet on top of the ripples and marked off the crests with a grease pencil. Using this method, ripple heights could only be estimated, and the problem of ripple distortion by the Plexiglas® was always present. Furthermore, reliability decreases markedly when the current velocity increases because of scour around the sheet and the diver's inability to hold position long enough to mark the Plexiglas®.

Underwater surficial mapping requires identification and delineation of the materials and features that compose the seafloor. In a small area, this can be accomplished more accurately by a diver at the underwater site than by instruments from a surface craft. Surficial features (such as rock outcrops, coral reefs, unconsolidated sediment, and textural and compositional variations in the sediment) must be

Figure 9-24
Box Cores (Senckenberg) for
Determining Internal Structure in Sand



Taking and processing of sand box cores to identify internal structure. **a**—Senckenberg boxes aligned in a series shown here as normal to a northtrending shoreline (L). Box #1 is nearly completely emplaced boxes #2 and 3 partly emplaced. Spiral anchor screwed in sand behind boxes provides stability and leverage for diver. **b**—Box filled with sand bottom plate secured with elastic band. Box sides were taped together prior to sampling to prevent their spreading apart during emplacement. **c**—Box on side in laboratory bottom plate removed. **d**—Upper side of box detached and uppermost 2 to 3 cm of sand removed by careful troweling. **e**—Metal tray inverted and pushed into sand surface. Orientation data transferred to tray. **f**—Tray removed and sand leveled and dried. Orientation data on underside of tray. **g**—Sand within tray impregnated with about 120 cc of epoxy resin. When resin has set orientation data is transferred to the sand slab. **h**—Sand slab removed from tray internal structure outlined by surface relief provided by preferential penetration of resin through individual beds. Orientation data on underside of slab

Source: NOAA (1979)

identified, and their distribution must be traced and plotted to scale.

The problems of locating underwater features accurately and of covering a sufficiently large area can be minimized by towing the diver-observer with a surface craft equipped for precise navigation and communication with the divers. To ensure accurate location of features, the towed diver should mark the features with a float. In areas where the bottom can be seen clearly from above water, aerial photographs are useful to establish the general bottom configuration. The details can then be completed under water (Figure 9-27). Geologic mapping of the rocks that compose the seafloor is best accomplished by using seismic profiling techniques from a surface craft. If a specific question arises—such as the identification of a rock unit or the location of the

Figure 9-25
Greased Comb for
Ripple Profiling

Photo David Klise

Figure 9-26
Diver Using Scaled
Rod and Underwater Noteboard

Photo David Klise

surface trace of a fault—direct underwater observation must be used to answer it. For example, a geologist may need to know the attitude (strike and dip) of sedimentary strata or of fractures, joints, and faults in the rock.

The strike of a rock bed is the compass direction that the bed would make when projected to a horizontal plane on the earth's surface. To fix the orientation of the bed, however, it is also necessary to know the dip. The dip is the angle in degrees between a horizontal plane and the inclined angle that the bed makes, measured down from horizontal in a plane perpendicular to the strike. Dip is measured with a clinometer. These relationships are illustrated in Figure 9-28.

Rock outcrops on the seafloor may be located by noting irregularities in bottom profiles, anomalous shoals or reefs, or the presence of organisms such as kelp that normally grow on rocks. The rock outcrop may be so encrusted by bottom flora and fauna that recognition of features, such as stratification surfaces, fractures, and joint planes, is difficult. In such cases the diving geologist must clean off the encrustations, search for freshly scoured surfaces, or collect oriented samples in the hope of establishing the three-dimensional fabric of the rock in the laboratory. In some areas, differential weathering or erosion makes stratification surfaces and fractures more readily visible under water.

To measure the attitude of planar elements in the rocks, the diver needs an adequate compass with an inclinometer. Underwater housings can be built for the relatively large surveying compasses commonly used on shore. A hollow plastic dish almost completely filled with fluid (plastic petri dishes work well) and marked with perpendicular crosshairs on the flat surfaces is a useful adjunct to underwater mapping. The dish is placed in the plane of the feature whose attitude is to be measured and rotated until the enclosed air bubble coincides with a crosshair. The other crosshair, which is now horizontal, defines the strike of the feature, and the downward direction of the crosshair coincident with the bubble defines the dip and dip bearing.

Some outcrops are located in water too deep to be sampled by these methods unless the diver is operating in the saturation mode. Where underwater sampling cannot be done, a photograph of the outcrop that includes a scale (like the one in Figure 9-29) can yield a considerable amount of information.

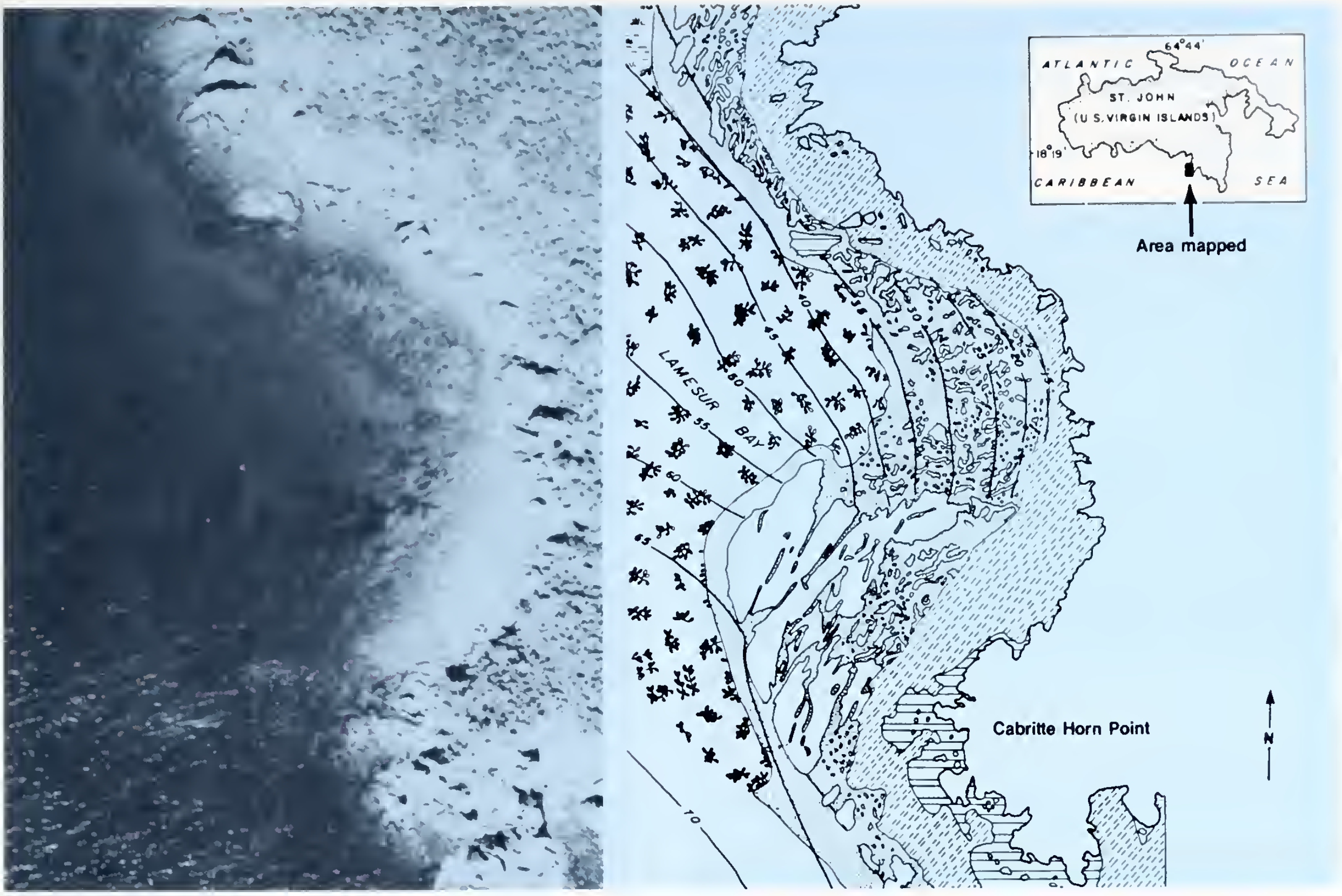
For any kind of underwater mapping, it is useful to prepare a base map on which the outlines of previously established features are drawn in indelible ink on a sheet of plastic material. New features can be sketched in pencil on the base and, as they are confirmed, inked onto the map.

9.10.2 Sampling

Diving geologists sample everything from unconsolidated sediments to surface and subsurface rock formations. Although standard land techniques can be used directly in a few underwater situations, they usually must be modified (or new techniques must be developed) to cope with the underwater environment. Diving allows selective sampling, which is not possible when using boat-based methods. The diver sees exactly what is collected and how it relates to other aspects of the submarine environment. Compromised samples can be discarded and easily replaced. Also, diving may be the only way of sampling the seafloor in areas, such as the high-energy surf zone, inaccessible to surface craft.

Rock sampling may be required in the compilation of an underwater geologic map or to answer other

Figure 9-27
Aerial Photograph and Composite Map



Courtesy U.S. Geological Survey

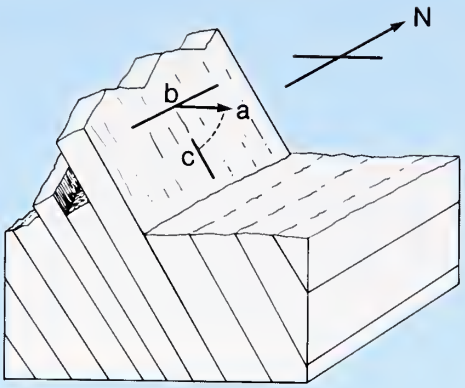
questions. Samples broken directly from the outcrop are the most reliable, although talus fragments may be adequate if they can be traced to a particular outcrop. Breaking through the external weathered or encrusted rind of a submarine outcrop may be difficult because water makes swinging a hammer impossible; a pry bar or geological pick can be used in existing fractures or can be driven against an outcrop with better effect. Explosives may be practical in some cases but must be used with extreme care (see Section 8.12). Pneumatic, electric, or hydraulic drills are available for underwater work (see Section 8.4).

Macintyre (1977) describes a hydraulically powered, diver-operated drill used in water depths up to 49 feet (15 m) (Figure 9-30). The drill consists of a Stanley hydraulic impact wrench (modified for consistent rotation) that is powered by a hydraulic pump on the surface. The drill rotates at a maximum of 600 rpm and provides sufficient torque to core under any reasonable conditions (Macintyre and Glynn 1976, Macintyre 1977). The unit will recover cores roughly 2 or 3.5 inches (5 or 9 cm) in diameter, using a double-walled core barrel.

Macintyre's original unit was powered by a Triumph 4-cylinder industrial motor, which limited the type of surface vessel used for support. Smaller units have been designed that utilize 5-10 hp motors. The result is a more portable unit, weighing about 350 pounds (159 kg), that can be operated from a small boat. Although this approach reduces the flow rate over that of Macintyre's original design, cores over 82 feet (25 m) in length have been retrieved with these newer systems (Halley et al. 1977, Hudson 1977, Shinn et al. 1977, Marshall and Davies 1982, Hubbard et al. 1985).

For use in water less than 6.6 feet (2 m) deep or on exposed reefs, a tripod is required to support the drill (Figure 9-30). In deeper water, a lift bag can be used in place of the tripod. Using the habitat *Hydrolab* in the U.S. Virgin Islands as a base, Hubbard and his coworkers (1985) were able to core horizontally into the reef face in water depths of 98 feet (30 m). On such deep operations, bottom time is usually the limitation. In addition to tending the normal operation of the drill, a diver is needed to monitor the progress of the coring and to note anything that would be useful in logging

Figure 9-28
Dip and Strike
of Rock Bed



Block diagram illustrating *dip* and *strike*. Direction of dip due east, shown by arrow; amount of dip, angle *abc*. Notice that arrow extends horizontally as it would if placed flat on a map. Direction of strike is north-south, shown by cross-arm of symbol; it represents a horizontal or level line drawn on inclined bedding plane.

Photo Holmes (1962)

Figure 9-29
Geologist Measuring
Dip (Inclination) of Rock Outcrop

Photo Larry Bussey

the core at the surface. A submersible drilling frame can solve some of these problems when divers are working in deeper water. Adjustable legs allow deployment on an irregular, sloping bottom. The frame securely holds the drill in place, while a lift bag can be used either to place pressure on the drill or to lift it out of the hole. By using a video camera, the drill can be monitored remotely, and divers are needed only to set up and recover the cores.

Figure 9-30
Coring in a Deep Reef
Environment With a Hydraulic Drill

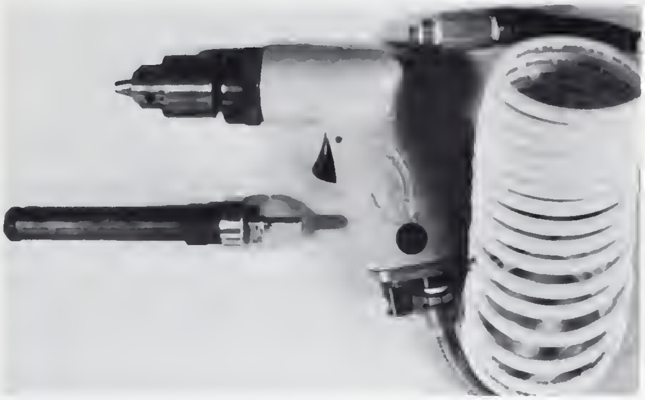
Photo Eugene Shinn

The hydraulic drill is also useful in obtaining shorter samples through large coral heads for the purpose of examining internal growth bands. A larger diameter, single-walled barrel is fitted to the same drill and is used to remove a plug from the coral colony. Because this method is meant to be non-destructive, great care must be taken not to damage the surrounding colony. Some researchers have inserted a concrete plug into the hole they have drilled to promote overgrowth of the colony by algae.

The drill (Figure 9-31a), which can operate at about 100 psi (7 kg/cm^2), is attached to a neoprene hose that is fitted to the low-pressure port of the first stage of a regulator, which is attached to a standard scuba cylinder. The drill bit is designed so that the core sample is forced up into the middle of a core barrel attached to the bit. This barrel, in turn, is designed to retain the core sample when the barrel is removed from the bit. The barrels containing the sample can be removed, and new barrels can be attached by the diver under water. The best cores can be obtained by running

Figure 9-31
Pneumatic Hand Drill

A. Drill and Attachment



B. X Ray of Core

Photo Collin W. Stearn

the drill at its maximum speed, with maximum pressure on the bit to make the hole quickly. When the full penetration of the bit is completed, a slight rocking motion of the bit in the hole will break the core free and permit it to be removed from the hole. Complete unfractured cores 0.39 inch (1 cm) in diameter and up to 33.5 inches (85 cm) long have been obtained with this method. A single 72 cubic foot (2 m^3) scuba cylinder is sufficient to drill 4 holes in the coral *Montastrea annularis* at depths up to 23 feet (7 m) (see Figure 9-31b). Because this equipment is not designed for use in salt water, extra care must be taken after use to rinse and clean it to avoid corrosion. Further details concerning this technique can be found in Stearn and Colassin (1978).

Sampling unconsolidated sediment generally is easier than sampling solid rock, but it may also present problems. The collection technique used depends on the purpose of the study. For example, if samples are collected for compositional or textural analysis, the primary concern is to obtain material representative of a larger entity. On the other hand, if internal structure or engineering properties are the goal, the sample should be as undisturbed as possible (see Section 9.10.2).

Collecting a representative sample creates a number of problems that must be resolved. For example, how deep below the surface should the sampler penetrate? The sediment beneath the seafloor may have been deposited under conditions markedly different from those producing the surface sediment; if so, its character will differ accordingly. How does one sample a sediment containing interlayered sand and mud? How large a sample is required to be representative of a specific particulate trace component, such as placer gold, without biasing the sample by the loss of some component, such as the finest or densest material? Many of these questions have been addressed in conjunction with subaerial sampling, and the techniques employed in this form of sampling are applicable to underwater sampling as well (Clifton et al. 1971).

Surficial samples taken with a small core tube circumvent many sampling problems and permit a highly consistent collection program. Plastic core tubes several centimeters in diameter with walls a millimeter or so thick are ideal and inexpensive. Cut into short tubes several centimeters long, they can be numbered and have rings drawn (or cut) on them 0.39 to 0.78 inches (1 to 2 cm) from the base and top (depending on the thickness of the sediment to be cored). Two plastic caps for each tube complete the assembly. The tubes are carried uncapped by the diver to the collection site. A tube is pushed into the sediment until the ring on the side coincides with the sediment surface, and a cap is placed carefully over the top of the tube. Its number is recorded, along with a description of the sample location. A trowel or rigid plate is slipped under the base of the tube, and the tube is then removed from the sediment and inverted. The second cap is placed on the base, and both caps are secured. This simple arrangement can be improved by adding a removable one-way valve to the top end and a removable core catcher to the bottom. These items allow the diver to insert and remove the core without capping it. Capping is done at a convenient time, and the end pieces are then transferred to another tube for reuse.

An inexpensive alternative to a core tube is to cut one end off a 50-cc disposable syringe and to use it as a small piston core. The sampler is pushed into the sediment while the syringe plunger is being withdrawn slowly to keep the sampler at the sediment surface. The plunger provides enough suction to permit the small sampler to be removed quickly from the bottom without losing any sediment. The sample can then be extruded into a sample bag, or it can be kept in the core tube by capping the tube with a small rubber stopper.

Undisturbed samples of seafloor sediment are valuable for identifying internal structures, such as stratification or faunal burrows, and for making measurements of certain engineering properties. Compared with the brief view of the seafloor possible during a single dive, analysis of these structures provides a broader perspective on processes through time. Internal stratification, considered in light of sediment texture, can be used to infer the strength of prevailing currents during the time of deposition. The orientation of cross-stratification indicates the direction of the stronger currents in the system and may indicate the direction of sediment transport. The degree to which mixing by faunal burrowing disrupts these structures is indicative of the rate of production or stratification, which in turn reflects the rate of the occurrence of physical processes and/or the rate of sedimentation.

Internal structures of modern seafloor sediment also provide a basis for interpreting ancient sedimentary environments. Direct comparison of depositional features in a rock outcrop with those in an individual core may be difficult because of the limited view permitted by a core. This problem can be overcome, to a degree, by taking oriented cores in an aligned series, which yields a cross section that is comparable with that in the outcrop.

The collection of undisturbed samples from the seafloor requires special coring techniques. Diver-operated box cores have been used successfully to core the upper 3.9 to 7.8 inches (10 to 20 cm). Cans or similar containers from which the bottoms have been removed are useful in muddy sediments. With their tops off, they can be pushed easily into the mud until the top is at the sediment surface level (the surface layer can be lost if the container is pushed below the sediment surface). The opening at the top of the container is sealed by a screw cap or stopper after the can is emplaced in the sediment, and the sediment remains intact as the core is withdrawn. A wedge-shaped or spade corer permits the taking of somewhat larger surficial cores.

Cores can be taken in sandy sediment with a variety of devices, ranging in design from very simple to quite complex. Cores more than 6.6 feet (2 m) long can be taken by driving thin-walled tubing several centimeters in diameter into the sediment. A simple apparatus consists of a removable collar that can be attached firmly to a 3 inch (7.6 cm) in diameter thin-walled irrigation pipe. A pounding sleeve consisting of a 3 inch (7.6 cm) inside diameter pipe with two pipe handles welded to it is slipped over the irrigation pipe above the collar. By forcefully sliding the pounding sleeve down onto the collar, a 3.3 to 6.6 foot (1 to 2 m) core can be taken (the core tube must be long enough to allow for the core and enough pipe above the collar to slide the pounding sleeve). Adding a removable piston attached to a stationary pole so that the piston remains at the sediment surface during coring can increase the penetration of this apparatus to several meters. Recently, scientists have constructed a coring apparatus that used a hydraulic jack hammer. The jack hammer is attached to one end of a section of 3 inch (7.6 cm) in diameter aluminum irrigation tubing cut into the necessary lengths. The attaching device is a slip-fit made by press-fitting a collar to a standard jack hammer chisel shaft. Slits are also cut into the upper 6 inches (15.2 cm) of the core tube to allow for the escape of water. During operation, the entire device is suspended in the water with an air bag or air-filled plastic garbage can. Holding the core pipe in a vertical position, the diver releases air from the air bag and descends slowly until the tube makes contact with the bottom. After ascertaining that the core tube is oriented vertically, the trigger is pressed and the tube is jack-hammered into the bottom. Generally, 19.7 feet (6 m) of penetration is attained in about 30 seconds. Experience has shown that loss due to compaction is less than 10 percent. Cores up to 29.5 feet (9 m) in length have been obtained using this method.

A different type of apparatus used for underwater coring is the vibracore, which relies on high-frequency vibrations rather than pounding to push the core tube through the sediments. The core tube is driven as deeply into the bottom as possible and is then extracted; during extraction, the vibration source is turned off. Several excellent but costly commercial units are available; a less-expensive unit can be constructed by attaching a simple concrete vibrator to the top of a 3 inch (7.6 cm) piece of irrigation pipe. The unit can be powered by a small motor located in the support boat; cores 32.8 feet (10 m) long have been taken with this type of unit.

Subaqueous cores are saturated with water when they are removed from the bottom and must be handled carefully to avoid destroying them. For example, unless great care is taken, the sediment may be washed from the corer as it is removed from the water, be liquefied by excessive agitation, or collapse during removal from the corer. The careful geologist avoids these frustrations by planning core retrieval and transport as an integral part of the coring system.

Other types of geologic samples can be collected by divers. For example, gas escaping from seafloor seeps may be collected more easily by a diver/scientist operating at the seafloor site than by scientists working from a surface craft. Hydrocarbons in the sediment can be analyzed with greater precision when the samples have been taken by divers. These containers can be sealed immediately after sterilization, be opened under water, and then be resealed with the sample inside before being returned to the surface.

9.10.3 Testing

In the context of this section, testing means determining some variable of the sediment in situ that cannot be identified accurately on the surface from a sample of the same sediment. For example, Dill and Moore (1965) modified a commercial torque screwdriver by adding a specially designed vane to the shaft. The vane was inserted carefully into the sediment, and torque was slowly and constantly increased until sediment failure occurred (Figure 9-32). From this simple test, these authors were able to determine the maximum shear strength of surface sediments. They also measured the "residual strength" of the sediment by continuing to twist the dial after initial shear occurred. Use of this equipment generally is restricted to currentless locales because the diver has to remain motionless during the test to be able to operate the apparatus correctly and accurately.

Figure 9-32
Diver Taking
Vane Shear Measurement

Photo Lee Somers

9.10.4 Experimentation

The underwater environment is a superb natural laboratory, and diving permits the geologist to study a number of processes in real-time experiments. Most studies of this type begin with a careful characterization of the study area, followed by an experiment (usually carried out over an extended period of time) designed to explore the interrelationships among geological, biological, physical, and chemical processes.

The experimental technique may be simple or sophisticated, depending on the nature of the phenomenon studied and the resources of the experimenters. Repeated observations at a selected site can produce much information on processes, such as bed-form migration or bed erosion and deposition. When visibility permits, real-time video, cinephotography, or time-lapse photography produces a permanent record of an ongoing process that can later be analyzed in great detail. Monitoring a site with sophisticated sensors can, for instance, yield quantitative information on the interaction of pertinent physical and geologic variables.

Since many experimental studies in nature involve making serial observations of the same site, the experimental site may have to be reoccupied to continue the study or to service equipment. Relocating the site can be difficult and must be planned ahead of time. A buoy, stake, or prominent subaqueous landmark may suffice in clear, quiet water, while more sophisticated equipment such as sonic pingers (see Section 8.3) may be needed under adverse conditions. Current technology has advanced to the point where Loran C navigation systems can guide a boat to within less than 20 feet (6.1 m) of a previously visited site. Such units are readily available and can be used on small boats. Surface buoys tend to arouse the curiosity of recreational boaters, who may tamper with or even remove them, and landmarks are seldom close enough to the actual site to be useful, especially when visibility is poor. Emplacing stakes at the actual site must be done carefully so as not to alter the current flow enough to compromise experimental results.

Some experiments involve the emplacement of unattended sensors that monitor conditions at specific times or whenever certain events occur. The data from such sensors are either recorded in situ or transmitted by cable or radio to a recording station. Relocation is necessary to maintain or recover the equipment used in such experiments.

Characterization studies will continue to be the mainstay of underwater geologic research because most of them can be completed without elaborate equipment. In-situ experimental studies, however, will undoubtedly become increasingly important as more geologists discover the advantages they offer in answering fundamental questions about the geologic environment.

9.11 MICROPHYSICAL OCEANOGRAPHY

Micro-oceanographers have so far not taken full advantage of diving techniques; to date, in-situ measurements and observations of water mass processes have not been widely used. Turbulent cells, boundary layers, and flow regimes have not been studied extensively. Notable among published accounts are the studies of visual indications of the thermocline, the use of dye tracers to reveal flow patterns (Woods and Lythgoe 1971), and the study of internal waves and the formation of bubbles in sound attenuation (LaFond and Dill 1957). Work by Schroeder (1974) in *Hydrolab* has shown that divers can be used to do more than emplace, tend, and recover oceanographic instruments. Divers are the best means of ascertaining the scale of measurements of the physical nature of the water column. The oceanographic scientist today dives to implant instruments in the active parts of the water column and to ensure that these instruments are measuring the real underwater world.

Table 9-1 summarizes some of the micro-oceanographic variables and problems that involve the use of divers in data collection. As better methodology develops, the diver's role in micro-oceanography will expand.

9.11.1 Emplacement and Monitoring of Instruments

The implantation, reading, and maintenance of instruments and instrument arrays and the recovery of samples and data are important jobs divers can perform in oceanographic surveys. Instruments implanted at a site to measure current flow, direction, or other phenomena may be damaged by marine growth or the buildup of sand or bottom debris. If the instruments are read remotely, these conditions may alter the validity of the data measured by the instrument. Divers should routinely check the condition of implanted instruments to ensure that they are operating correctly.

Undersea laboratories are of great advantage in experimental studies requiring the use of many instruments and dives of long duration. The Undersea Instrument Chamber (USIC) provides a stable underwater housing for instruments that record oxygen, temperature, light, pH, conductivity, and sound. The USIC can be entered by divers as necessary for data retrieval equipment, calibration, and monitoring (Figure 9-33).

A good diver-managed oceanographic instrumentation program was carried out during a *Hydrolab* underwater habitat mission in 1972 (Schroeder 1975). The objective was to evaluate a continuously deployed shallow-water current and hydrographic monitoring system. Divers set up thermometers, current meters, pressure gauges for tidal measurements, and instruments for measuring depth, temperature, conductivity, salinity, dissolved oxygen, and pH using a taut line buoy array. Data were obtained by reading the instruments and/or by a direct readout display inside the habitat. When reading a vertical array of the thermometers, the procedure was to swim at an angle to the top thermometer, read it, and then to descend the buoy line to read the remaining thermometers. The data were transferred onto a slate secured to the anchor weight of the buoy system. This procedure prevented the aquanaut's exhalation bubbles from disrupting the thermal structure.

Figure 9-33
Undersea Instrument Chamber

Photo Morgan Wells

Table 9-1
Micro-Oceanographic Techniques

Variable	Instrument/ Technique	Diving Mode*	Placement	Problems	Remarks
Temperature	Thermometer array	C,S	Taut-line buoy, pier, piling, oil rig.	Where to position thermometers. Pre and post use calibration. Requires repetitive observation.	Limited by bottom time in conventional modes.
	Recording thermograph	C,S	Same as above but secure to bottom.	Equipment flooding. Electronic failure. Only one data point unless multiple units used.	Relocation of units.
	Remote readout	C,S	Same as above.	Same as above.	Excellent for use in habitat.
Salinity	Water samples	C,S	Bottle rack carried by diver.	Number of samples. Processing procedures.	Limited by bottom time in conventional modes.
	Recording salinometer	Same as for Temperature, above			
	Remote readout	Same as for Temperature, above			
Dissolved Oxygen	Water samples	C,S	Bottle rack carried by divers.	Outgassing when brought to surface.	Best used from a habitat.
	Remote readout	Same as for Temperature, above			
Multiple Sensor Unit	Recording	Same as for Temperature, above			
	Remote readout	C,S	Reverse vertical profiling using floats and pulley system.	Fouling of cables. Interface at surface.	Excellent for habitat operations.
Currents	Recording	Same as for Temperature, above			
	Remote readout	Same as for Temperature, above			
	Dye studies				
Tides	Recording (waves)	Same as for Temperature, above			
	Ambient pressure gauge inside habitat	S	Gauge inside habitat.		

*C=conventional diving
S=saturation diving

Source: NOAA (1979)

9.11.2 Planktonic Studies

Diving techniques have long been an integral part of in-situ experiments on the effects of controlled nutrient enrichment of phytoplankton and zooplankton populations. In Lake Michigan, divers implanted large plastic bags at various depths, which required placement of a screw-type anchor or other anchoring device in the lake bottom and attachment of a collapsed bag held in a vertical position by a submerged float (Somers 1972). Divers could then insert a hose into each bag to facilitate filling with lake water and nutrient solutions. After the filling process was completed, the divers disconnected the hoses and secured the filling tubes. Water samples were taken periodically by divers using a hose and pump.

The role of zooplankton in a coral reef system was studied by divers working from the *Hydrolab* underwater habitat during three saturation missions (Schroeder et al. 1973). Plankton samples were obtained by divers using small nets attached to a hand-held diver propulsion vehicle (see Section 9.5.1). Several variations on this technique have been used and are described in Schroeder (1974). To quantify the volume of water filtered by the sampling nets, the area of the net mouth was multiplied by the distance traveled. Samples were preserved by pouring the contents of the cod end of the net into a jar filled with filtered seawater and sealing it with plastic wrap. The sample was then preserved by injecting formalin through the plastic by syringe and capping the jar immediately.

A second method of sampling zooplankton in inaccessible areas, such as small caves in coral, involves a suction system utilizing air from a scuba tank to create a vertical water current in a 7.9 inch (20 cm) plastic tube with a plankton net secured to the top. When used properly, the device is capable of capturing even fast-moving small reef fish.

9.11.3 Use of Dye Tracers

In addition to the emplacement and monitoring of instruments, divers have used dye tracer techniques to measure currents, internal waves, thermoclines, and various turbulent components of the water column (Woods and Lythgoe 1971). Water masses tagged with fluorescein dye can be followed and photographed to provide an accurate measurement of current speed and direction. If a point source of dye (a bottle full of dyed water) is released into the current, accurate measurements can be made at speeds lower than those of most current meters commonly employed. To understand the generation of turbulence inside a thermocline and within the water column, it is necessary to know both the density gradient and the *velocity shear*. The most convenient technique for laying a shear streak is to drop a tiny pellet of congealed fluorescein through the layer under study. Disk-shaped pellets, 0.12 inch (3 mm) in diameter and 0.6 inch (1.5 mm) thick, are particularly useful. These pellets are attached to a light line and dropped through a thermocline. The dispersion of the dye by the ambient flow can then be photographed.

The only disturbance to the existing flow caused by the pellet's passage through the water column is caused by the formation of a small vortex wake, whose individual vortexes rapidly lose their own motion and follow the ambient flow. The pellets are sealed in waterproof polyethylene strips until needed. Three sizes, each with the same aspect ratio, are used: the smallest, described above, gives the most regular wake but lasts only for about 5 minutes. The largest, 0.24 inch (6 mm) in diameter by 0.09 inch (2.3 mm) thick, can lay a streak through the whole thermocline. The speed of these pellets is comparable to the difference in horizontal velocity encountered along any streak, and their drop path is often quite complex, which means that the velocity profile cannot be determined from a single photograph. Instead, the mean shear across any given layer is obtained in successive frames of a timed sequence of still photographs or motion pictures.

The general procedure is as follows: after identifying the area of interest by dropping a trial pellet, the photographer positions himself or herself above the chosen level and then signals an assistant who is floating above and upstream to release a second pellet. As the second pellet begins to fall, the assistant increases his or her buoyancy, which permits the assistant to move away from the dye streak without disturbing it. Whenever possible, the assistant is positioned above the sheet overlaying the layer being filmed; this sheet isolates the assistant's movements from the dye. The photographer then films the dye streak, keeping the sun behind the camera to increase contrast.

Current can also be measured near the bottom by using dye tagging techniques (Figure 9-34). Care must be taken not to kick up sediment or to create artificial vortexes by swimming in the area during such studies.

9.11.4 Water Samples

When taking measurements or samples in the water column, care should be taken to minimize the amount of activity around the study sites to avoid unnecessary mixing of the water column caused by vertical water currents from the diver's exhaled bubbles. Instruments should be placed well away and upstream of all bubble activity.

Divers can collect bulk water samples by swirling large plastic bags through the water until filled, sealing the mouths of the bags, and carrying the bags to the ship. Because large water samples are heavy, the bags should be put into rigid underwater containers that are then attached to the boom of the ship. The plastic bag sampler can be modified to collect more precise water samples by gluing or stapling a strip of wood or plastic to each edge of the bag opening, so that it will extend from the corner to about two-thirds the length of the opening. The remaining third of the open end is then

Figure 9-34
Dye-Tagged Water Being
Moved by Bottom Current

Courtesy U.S. Navy

folded back against one of the supports and lightly closed with tape or a rubber band to prevent water from entering the bag. To begin sampling, the diver pulls the two mouth supports apart, breaking the tape or rubber band, and opens the bag to form a triangular mouth. The bag will fill entirely as the diver pushes it forward. The diver then closes the supports, refolds the loose end back against one of the supports, and rolls the edge tightly toward the bottom of the bag to seal in the water sample. Large plastic bags also can be filled using hand-operated pumps. When shipboard analysis requires uncontaminated samples, new, acid-washed, hand-operated plastic bilge pumps can be used to collect samples.

Smaller water samples, up to 1.06 quart (1 L), can be taken with extreme precision using a plastic or glass jar with a 2-hole stopper, one hole of which is fitted with a flexible sampling tube of selected length and diameter. At the desired depth, the diver inverts the unstoppered jar, purges it with air, and then inserts the stopper. The jar is then righted and, as the air bubbles out of the open hole in the stopper, the diver manipulates the sampling tube to vacuum the water sample, organisms, or detritus into the jar. After evacuating all the air, the diver seals the jar by inserting the tip of the sampling tube into the open hole of the stopper or by swiftly replacing the stopper with a cap. A bubble of air remains in the top of the sampling jar and is replaced with water when the stopper is removed. Contamination is generally insignificant. Bottles larger than 1.06 quart (1 L) are inconvenient because the buoyancy of the air-filled jar is sufficient to disturb the buoyancy of the diver, requiring constant attention to depth regulation and distracting the diver from the task at hand. When standard ship-operated water samplers are used, the divers and ship personnel can precisely position and trigger the samplers under water.

It is difficult to obtain accurate measures of dissolved oxygen in seawater because the changes in pressure to which a sample of seawater is subjected as it is brought to the surface affect the chemical nature of the solution. Liquids and solids are relatively insensitive to pressure effects, but dissolved gases are sensitive to pressure changes. Even if the container is protected as it is raised through the water column, oxygen may be taken up when the container is opened on the surface. To overcome this limitation, a sampler that is portable, versatile, and inexpensive has been developed (Cratin et al. 1973). This sampler and technique are equally effective for operations from the surface or from an ocean floor laboratory.

The sample bottles (Figure 9-35) are constructed from PVC tubing that is 2.4 inches (60 mm) o.d., 1.9 inch (48 mm) i.d., and 4.7 inches (12 cm) long, which provides a volume of about 0.24 quart (225 ml). Screw caps made of plastic and fitted with PVC inner linings and rubber O-rings effectively seal both ends of the sample bottle from their surroundings. A hole, 0.59 inch (15 mm) in diameter, is drilled into the side of each sampler and a piece of PVC tubing 0.59 inch (15 mm) long is sealed into it. Finally, a rubber membrane is fitted into and over the small PVC tubing. When taking large numbers of samples, a backpack designed to fit over double scuba tanks is a useful accessory (Figure 9-36).

A sample collection proceeds as follows: the open bottle, i.e., without the screw caps, is moved to the underwater location, tapped several times to ensure complete removal of all trapped air, and one of the caps is screwed on. A marble is placed into the sample bottle and the second cap is then screwed firmly into place.

To prevent oxygen from ongassing when the sample is brought to the surface, two chemical "fixing" solutions are added in the following manner: a venting (hypodermic) needle is placed into the membrane and .0042 pint (2 ml) of manganese (II) sulfate and alkaline potassium iodide solution are injected into the bottle by hypodermic syringe. (Special care must be taken to make certain that no bubbles of air are present in any of the syringes.) The bottle is shaken several times to ensure complete mixing. (The dissolved oxygen gas is converted through a series of chemical reactions

Figure 9-35
Diver Using
Water Sample Bottle

Source: NOAA (1979)

Figure 9-36
Water Sample Bottle Backpack

Photo William L. High

into a white insoluble solid—manganese III hydroxide.) When the samplers are taken to the laboratory, they must be kept under water as added insurance against leakage.

Once in the laboratory (with the bottle still under water), a venting needle is inserted into the membrane and .0042 pint (2 ml) of concentrated sulfuric acid is added via a hypodermic syringe. The bottle is shaken several times to ensure complete reaction. The sampler is then removed from under the water, one of the caps is carefully unscrewed, and known volumes of solution are withdrawn. A knowledge of the volumes, concentrations of reacting chemicals, and other pertinent data enables the analyst to calculate quantitatively the oxygen content in seawater. Use of this sampling technique is limited only by the depth at which a diver may safely work. Oxygen analysis of samples taken from much greater depths requires more complicated and expensive equipment that can be operated remotely.

9.12 ARCHEOLOGICAL DIVING

Over the last 20 years, diving methodology and technology have had an enormous impact on the scientific development of underwater archeology in the Americas (Burgess 1980). Archeological procedures developed in the 1960's for use on shipwrecks in the Mediterranean by Bass (1966, 1970, 1972, 1975) and his associates have been adopted and modified by professional archeologists in the United States to study both submerged prehistoric and historic sites. Since then, many archeologists have conducted historical and/or anthropological research on shipwrecks. Thousands of recreational divers and professional salvors have also become involved with wreck diving in their search for historic artifacts. As more people have discovered the adventure and monetary rewards of shipwreck diving, government resource managers and scientists have become increasingly aware of the need to preserve and protect historic shipwrecks.

Although this section deals primarily with shipwreck archeology, research on prehistoric remains that are under water is conducted for other purposes as well. For example, extensive work has been done in Warm Mineral Springs (Cockrell 1978) and Salt Springs (Clausen 1975), Florida, to depths of more than 200 feet (61 m), to obtain information on the area's early animal and human inhabitants, who date back more than 10,000 years. Figure 9-37 shows a diver recovering Indian artifacts off the coast of California.

The real boom in archeological diving in the United States has involved shipwrecks. It is estimated that, of the more than 2.5 million certified recreational divers in the country, about 200,000 are wreck divers. In addition to recreational divers, there are more than 1000 active salvor divers in the country. Professionally trained marine archeologists, who number no more than 100 in the United States, thus comprise the smallest group of wreck divers.

It is estimated conservatively that there are well over 100,000 shipwrecks in United States waters. Available data indicate that close to 90 percent of known shipwrecks on the Continental Shelf are located in depths of less than 60 feet (18.3 m). Along some parts of the coastline, shipwrecks are clustered in large numbers within a few hundred meters of the beach. Most harbors and inlets are rich in shipwreck sites. The Great Lakes, rivers, estuaries, and navigable channels of the inland waterway also contain thousands of shipwrecks from many different periods.

Figure 9-37
Diver Recovering
Indian Artifacts

Courtesy Diving Systems International
Photo Steven M. Barsky

9.12.1 Shipwreck Location and Mapping

Underwater archeologists use many of the same techniques and much of the same equipment as other marine scientists. The two principal methods of locating shipwrecks involve the use of visual search and remote sensing techniques. Visual search procedures are discussed in Sections 8.2 and 9.1 to 9.3. Within the last decade, remote sensing techniques have become highly sophisticated with respect to locating and defining shallow water shipwreck remains scattered over miles of open ocean (Mathewson 1977, 1983, 1986).

Marine archeologists use a number of different techniques to survey underwater sites. The primary objective of these techniques is to obtain reliable measurements that accurately reflect the horizontal and stratigraphic relationships between different types of artifacts within overall artifact scatter patterns. Many of these mapping techniques, such as baseline offsets, artifact triangulation, plane table and grid mapping, and photomosaic surveys, are well-known procedures on land sites and are described in detail in archeological publications (see Sections 9.2.1 and 9.10.1). Although the method and theory of underwater archeology are similar to those used to conduct excavations on land, operating procedures for mapping sites can be very different because of underwater conditions. The best way for archeologists to learn how to modify these techniques is by borrowing from the experiences of marine biologists and geologists and by experimenting with various methods to ensure that reliable descriptive data are obtained.

9.12.2 Shipwreck Excavation

Every historic shipwreck presents unique problems with respect to the archeological methods required to excavate. The depositional environment of each site largely governs how shipwreck remains are to be uncovered and recorded in situ. No two wreck sites are exactly the same. Shipwreck discoveries made since the early 1960's along the coasts of Florida, Bermuda, the Bahamas, and throughout the Caribbean have shown that ancient wooden-hull shipwrecks do not stay intact for as long as formerly believed. Shallow water shipwreck remains are subjected continuously to the onslaught of the sea. Because the vessels' superstructures are degraded by the impact of currents, storms, and shifting overburden, visual remains often are not easily recognizable on the sea bed. The ship's contents, along with its ballast and lower hull structure, may be covered by tons of sand, mud, or coral. Figure 9-38 shows a marine archeologist exploring the wreck of the *Golden Horn.*

Before excavation, it is essential to determine the general character of the environment, which helps to make the operation more efficient and to avoid unnecessary expenditures, accidents, and mistakes. Examples of the environmental and logistical information needed include:

- Measurements of the bottom topography and rates of sedimentation to determine the type of excavation equipment needed
- Sub-bottom profiles to determine sediment layers relative to wreck or site, and/or coring requirements
- Number of work days and best time of year to work at the site and the weather conditions to be expected
- Movement of suspended materials, underwater visibility, wave action, current, and temperature
- If near shore, usefulness of shore area as land base, work area, and living area.

Figure 9-38
Archeologist Exploring
the Golden Horn

Courtesy Diving Systems International
Photo Steven M. Barsky

Before excavation, all possible information about the attitude and extent of a shipwreck and its cargo must be known. Once the preliminary survey has been completed, a site excavation plan is formulated and systematic layer-by-layer surveying and artifact removal can begin. Care is needed to avoid damaging the artifacts or removing them without documenting their position; archeological excavation requires technique, appropriate equipment, and a great deal of patience.

Excavation methods range from hand-fanning with pingpong paddles to the application of large-diameter prop washes, more commonly referred to as deflectors or "mail boxes." Each digging procedure has its own advantages and disadvantages.

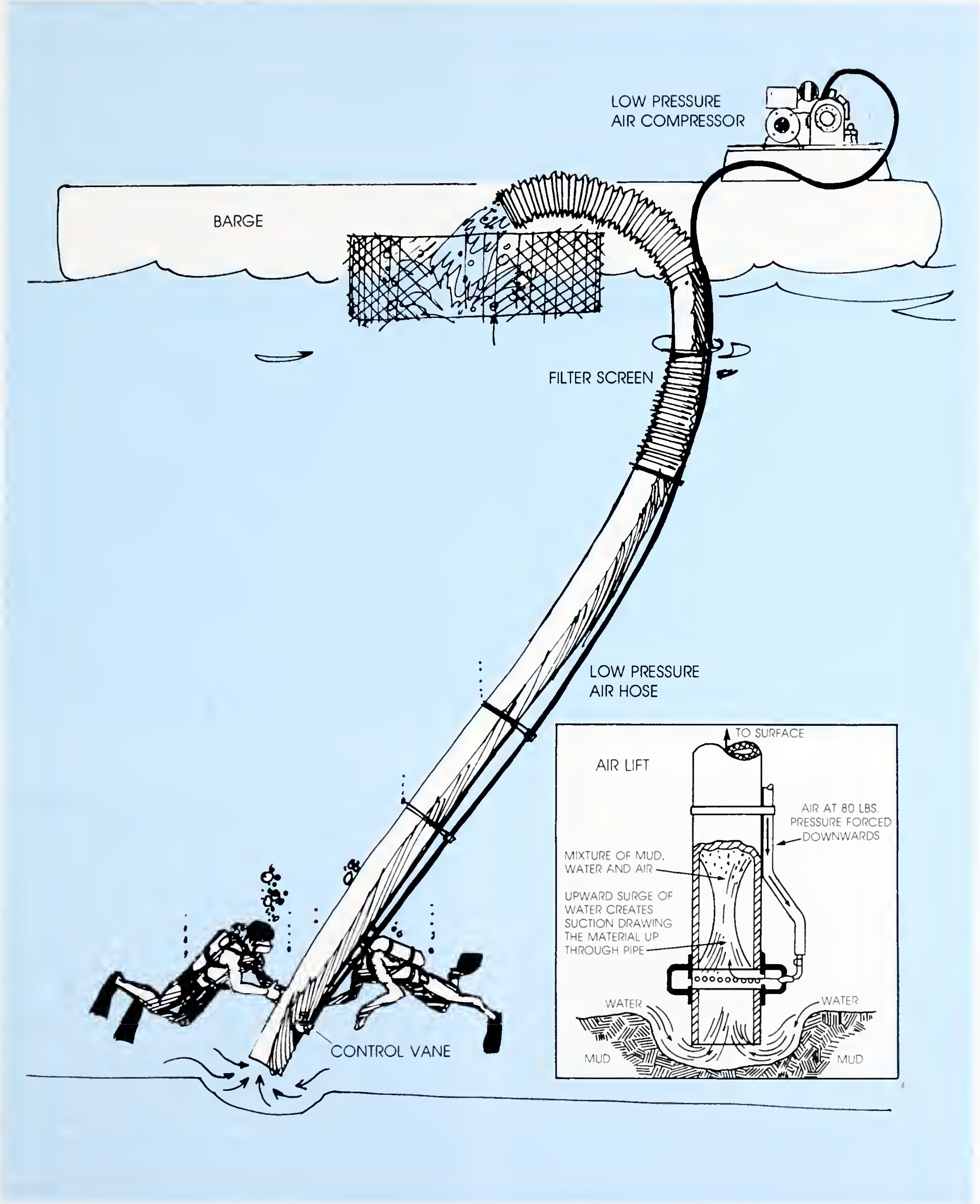
Airlift excavation involves the use of a long discharge pipe (usually made of PVC or aluminum) and an air manifold bottom chamber (Figure 9-39). Although the size of the airlift can range anywhere from 3 to 14 inches (7.6 to 35.6 cm) in diameter, airlifts with a diameter greater than 8 inches (20.3 cm) are very difficult for individual divers to handle. When deep sand or mud needs to be removed from a wreck site, the larger diameter pipe is more effective. When uncovering fragile artifacts, particularly in the presence of large amounts of organic matter, however, a 3 or 4 inch (7.6 or 10.2 cm) airlift is essential. The principle of airlift operation is described in Section 8.9.2.

Airlift efficiency increases with water depth because the trapped air expands as it ascends in the pipe; airlifts are consequently not very effective in water depths of less than 15 feet (4.6 m). Exploratory test holes 6 feet (1.8 m) deep and 10 feet (3 m) in diameter can be dug quickly with a 6 inch (15.2 cm) airlift in 45 feet (13.7 m) of water to define the perimeter of a site. When excavating around fragile artifacts, the airlift should be used more as an exhaust for removing loose overburden than as a digging instrument. Instead of using the suction force of the airlift to cut into the sea bed, divers should expose artifacts by carefully hand-fanning the bottom deposits into the pipe. In this way, fragile artifacts can be uncovered without being sucked up the pipe. Because even experienced divers lose artifacts up the pipe, the use of a basket or grate at the other end is essential. The most common problem with airlifts is that large pieces of ballast, coral, or bedrock get drawn into the mouth of the pipe and become jammed as they ascend.

Water jet excavation involves the use of a high-pressure water pump, a fire hose long enough to reach the sea bed, and a tapered nozzle. The nozzle should have small holes for permitting a backward thrust of water to eliminate the recoil so that the operator can stabilize the hose. The water jet creates a high-pressure stream that can cut through and remove hard-packed clays and sand, but its use as an excavating tool is limited to situations where the water jet will not damage artifacts or the integrity of archeological deposits before they are mapped.

The venturi pump excavation technique, sometimes referred to as a Hydro-dredge, involves the use of a 10 foot (3 m) length of metal or PVC tube, 3 to 6 inches (7.6 to 15.2 cm) in diameter, that is bent in a 90° elbow at the suction end. A hose from a high-pressure water pump on the surface is attached to the elbow juncture at the end of the tube. When high-pressure water flows along the length of the tube, a venturi effect causes a suction, which draws bottom sediment into the tube and out the other end, where it is discharged off the site. This excavation technique is ideal in shallow water, particularly in areas that are not accessible to the large

Figure 9-39
Heavy Overburden Air Lift



Courtesy: NOAA (1979) and Duncan Mathewson vessels needed to support airlifts or a prop wash. In water over 50 feet (15.2 m) deep, a similar hydraulic dredging tool called a Hydro-flo can be used by lowering it over the side and controlling it from the deck. As with all underwater excavation tools, hydraulic dredges must be used carefully to avoid damaging artifacts.

Prop wash excavation (also known as a "blower" or "mailbox") involves a 90° elbow-shaped metal tube mounted on the transom of a vessel (Figure 9-40). The metal elbow, slightly larger in diameter than the vessel's propeller, is lowered over the propeller, where it is locked into position. With the vessel anchored off the bow and stern, the engines are started so that the horizontal discharge of the water thrust that normally pushes the vessel forward is deflected downward. This surge of water blows away the bottom sediment. As successive overlapping holes are dug by shifting the position of the boat on its anchor lines, an archeological picture of the artifact scatter pattern slowly emerges.

The key to using the prop wash as an effective archeological tool is to control the engine speed properly. At slow speeds, the prop wash can remove overburden very delicately from wreck sites in 15 to 50 feet (4.6 to 15.2 m) of water without damaging the archeological integrity of the deposits. It can do great damage, however, if the engines are raced for too long a time. When operating a prop wash, experience and good judgment are needed to ensure that artifacts are not lost or damaged. It is essential to maintain good communication between the divers on the sea bed and the operator at the throttle to ensure safe, well-controlled excavation.

In proper hands, a prop wash can be very effective in defining the anatomy of a wreck site by determining the extent of its artifact scatter pattern. Even in deep sand, where it is impossible to record exact provenance data, artifact clusters mapped as coming from the same prop wash hole may aid in the interpretation of a site. Marine archeologists in Texas, Florida, North Carolina, and Massachusetts have successfully used prop washes to excavate wrecks.

The use of **flotation gear** is an inexpensive and effective method of lifting. Lift bags are available in different sizes and forms, ranging from large rubberized bags and metal tanks capable of lifting several tons to small plastic and rubberized nylon bags for lifting 50 to 500 pounds (22.7 to 226.8 kg). Larger bags should be equipped with an air relief valve at the top. For archeological work, smaller rubberized nylon bags are recommended; these self-venting bags have a lifting capacity of 100 pounds (45.4 kg) and are useful in all underwater operations. Lifting bags are described further in Section 8.9.1.

9.12.3 Artifact Preservation and Salvage Rights

The recovery of submerged artifacts is only the first step in enjoying the rewards of research, diving, and hard work. Many divers, either by accident or by design, recover valuable or historic artifacts, only to lose them because they do not take proper care of them. The first rule for preserving submerged artifacts is to keep them wet until proper preservation procedures can be initiated. If a diver is uncertain about what to do, he or she should consult local experts or publications on artifact treatment (Murphy 1985). Special preservation procedures are required for iron and steel artifacts, including the use of rust and corrosion inhibitors, acid treatment, sealants, chemical and electrolytic reduction, and encapsulation (Murphy 1985). Some of these techniques require soaking or treatments lasting weeks or months, depending on the nature and size of the artifact. Non-metallic artifacts must be preserved by the use of entirely different procedures.

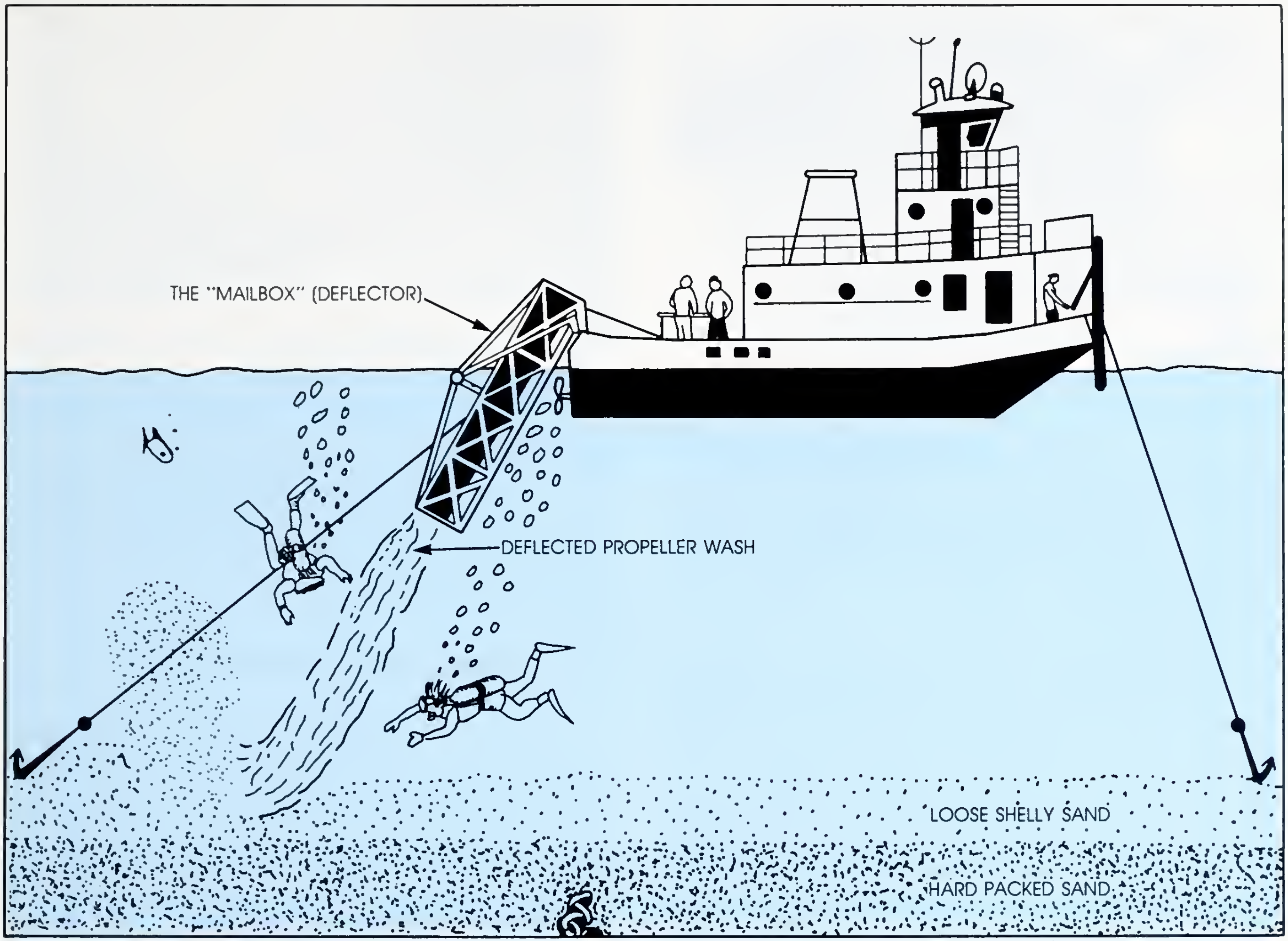
In addition to preserving artifacts, it is essential that the states and the courts establish the rightful ownership of artifacts recovered on submerged bottomlands. Generally, the U.S. Government controls operations on or under navigable waters, while the states own the waters and their submerged beds, which gives them authority over most finds. Non-navigable waters are usually privately owned or are controlled by local governments. There are many laws affecting the recovery of historical artifacts or the salvage of abandoned property, and these are often complex. Divers involved in such activities must be aware of applicable laws, both to protect themselves and their historical finds.

9.12.4 Significance of Shipwreck Archeology

The archeological significance of shipwreck sites is best determined by their physical integrity and their potential for providing historical and cultural data that are not available elsewhere. Information that can be gleaned from shipwreck sites includes: overseas trading patterns and maritime adaptation to New World cultural processes; maritime life styles and patterns of cultural change; and information regarding the evolution of European vessels and the development of New World shipbuilding techniques.

Like terrestrial sites, historic shipwrecks are not distributed on a random basis. The temporal and spatial patterning of shipwrecks is primarily a function of environmental factors, seafaring cultural traditions, maritime technology, and socio-political variables. Recent studies have demonstrated that the preservation potential for shipwrecks is highest in areas of low

Figure 9-40
Prop Wash System Used
for Archeological Excavation



Courtesy: Duncan Mathewson

energy (less wave action) and/or high rates of sedimentation. Thus, a knowledge of oceanography and aquatic geology is important when searching for submerged artifacts.

Shipwrecks should be considered not only as cultural resources but also as a source of valuable educational and recreational experiences. Wrecks to be explored for recreational purposes should be situated in clear water less than 30 feet (9.1 m) deep, have a visible hull structure, and be accessible by small boats. Heavily disturbed sites with little or no remaining physical integrity can, in certain cases, be used to teach students how to perform underwater archeological operations without distorting the archeological record (Mathewson 1981). Similarly, heavily disturbed sites and those of more recent date can be developed into archeological parks to provide new underwater experiences for sport divers. By promoting such recreational dive sites, user pressure on some of the more archeologically significant sites can be reduced.

9.13 ANIMAL CAPTURE TECHNIQUES

A wide variety of devices is used by scientists and commercial fishermen to aggregate, concentrate, or confine aquatic animals. Trawls, seines, traps, grabs, and dredges have all been used successfully by scuba-equipped scientists interested in animal and gear behavior. Diver-scientists who will be diving near such capture systems should train under simulated conditions before participating in open-water dives. Marine scientists can help to improve the design of trawls and other such equipment by evaluating its underwater performance, observing how animals behave in relation to the gear, and then conveying this information to equipment designers.

In the FLARE and *Hydrolab* undersea programs, divers were able to observe fish near stationary traps 25 to 80 feet (7.6 to 24.4 m) below the surface for up to 8 hours per day (Figure 9-41) and to devise methods to alter catch rates and the species captured (High and

Figure 9-41
Fish Trap

Source: NOAA (1979)

Ellis 1973). Divers from the National Marine Fisheries Service were also able to estimate accurately the populations of fish attracted to experimental submerged structures during studies designed to develop automated fishing platforms.

9.13.1 Nets

Nets vary in size, purpose, materials, and methods of use. Divers working close to an active net (one which is being towed) can interfere with its operation, especially if it is small, if they swim too near to it or touch it. Any net is considered large if direct diver contact does not appreciably influence its configuration or operation. Plankton nets typify small nets both in physical size and in the lightweight web required to retain micro-organisms. At the larger extreme, high-sea tuna seines often are 3600 feet (1098 m) long, with 4.5 inch (11.4 cm) long meshes stretching 200 feet (61 m) or more down into the water. Gill nets are designed to entangle fish attempting to push through the meshes; webbing mesh and thread size vary, as do net length and depth, in accordance with the size and species of fish sought. Gill nets use fine twine meshes hung vertically in the water between a corkline and a leadline. The net may be suspended at the surface or below the surface or be weighted to fish just above bottom and across the expected path of migratory fish. Divers and their equipment can easily become entangled in gill net webbing, which is difficult to see in the water.

9.13.2 Seines

Seines are similar to gill nets in that a wall of web is held open vertically in the water by the opposing forces of a corkline and leadline; however, the seine is set in a circle to confine fish within the web rather than to entangle the fish. Seines often have rings along the leadline through which a line or cable can be pulled to draw the bottom closed, which seals off the fish's escape route.

9.13.3 Trawls

Trawls are nets constructed like flattened cones or wind socks that are towed by one or two vessels. The net may be operated at the surface, in midwater, or across the seafloor. Specific designs vary widely, depending on the species sought. A 9.8 foot (3 m) long plankton net having a 1.6 foot (0.5 m) mouth opening may be towed at speeds up to 3.5 knots (1.7 m/s), while a 202 foot (61.5 m) long pelagic trawl with an opening 40.3 by 10.5 feet (12.3 by 21.5 m) may filter water at 1 knot (0.5 m/s). Figure 9-42 shows a trawl diver. Trawls may be opened horizontally by towing each wingtip from a separate vessel, by spreading the net with a rigid wooden or metal beam, or by suspending paired otterboards in the water to shear out away from each other horizontally when towed.

9.13.4 Diving on Stationary Gear

Diving on stationary gear such as traps, gill nets, and some seines presents few problems. Experienced divers can dive either inside or outside the net to observe animal behavior or to carry out work assignments. Divers must be alert to the entanglement hazard presented by loose diving gear, such as valve pull rods, valves, mask rims, knives, vest inflator mechanisms, and weight belt buckles. A buddy diver can usually clear the entanglement more readily than the fouled diver. Fouled divers must avoid turning or spinning around, which will entrap them in the web. It is occasionally necessary for a fouled diver to remove the tank, disengage the caught mesh, and replace the tank assembly before continuing with the task at hand.

9.14 THE USE OF ANESTHETICS IN CAPTURING AND HANDLING FISH

Anesthesia has been defined as a state of reversible insensitivity of the cell, tissue, or organism. In connection with fish, the terms narcosis and anesthesia are often used interchangeably, although not all chemicals characterized as fish anesthetics also act as narcotics. Anesthetics should be used for surgical intervention or to perform other painful manipulations. Fish anesthetics have been used in conjunction with a multitude of operations, including capture, transport, tagging, artificial spawning, blood sampling, moving fish in aquaria, surgical intervention, and photographic sessions. There is a wealth of published information in

Figure 9-42
Diver Checking Fish Trawl

Photo Ian K. Workman

the popular and scientific literature on a wide variety of chemicals and their applications.

The use of anesthetics does have an impact on the surrounding environment, and extreme care must be exercised to minimize this effect. The subsequent monitoring of an area in which anesthetics have been used must take this into account, because census and other data are affected by the use of anesthetics.

9.14.1 Response to Anesthetics

Fish anesthetics are administered most commonly by adding them to the water, which is then taken up by the gills. As the fish proceeds into anesthesia, it usually follows a series of definable stages that are useful to know in evaluating the depth of the anesthesia. A simplified scheme defining the levels of anesthesia, which is devised largely from the work of McFarland (1959) and Schoettger and Julin (1967), is presented in Table 9-2.

The response of a particular fish to an anesthetic depends on a number of factors, including the species and size of fish, water temperature, salinity or hardness, pH, and state of excitability of the fish, as well as on the dosage and type of anesthetic. With some anesthetics, not all of the stages mentioned in Table 9-2 are observable; for example, with quinaldine there is generally no definitive sedation stage. Recovery begins when the fish is removed from the anesthetic bath and transferred to untreated water, where recovery then proceeds, usually in reverse order, through the stages shown in Table 9-2.

9.14.2 Selecting an Anesthetic

Factors to consider in choosing an anesthetic are purpose, toxicity, repellent action, ease of application, and cost. It may be helpful to refer to the literature to choose a suitable anesthetic for the species and purpose concerned. In the absence of applicable data, it is often advisable to conduct a preliminary experiment, since even closely related species may not respond to the same anesthetic in the same manner. Species-specific intolerance has been demonstrated with some anesthetics.

Many chemicals exhibit toxic effects that are unrelated to their anesthetic action, and these may be transitory or sustained. Some chemicals that exhibit toxic effects during long-term exposure may be satisfactory to use for short-term anesthesia.

The therapeutic ratio TR = LC_{50}/EC is sometimes used in evaluating an anesthetic, where LC_{50} = the concentration lethal for 50 percent of the specimens and EC = the concentration necessary to provide the desired level of anesthesia. Generally, a TR of 2 or more is considered desirable, but since time of exposure and a variety of other factors affect the validity of the TR, its usefulness is somewhat limited.

The toxicity of the anesthetic to humans also must be considered. A given anesthetic may be dangerous to handle because of its acute toxicity or carcinogenic potential, or it may toxify fish flesh, rendering it dangerous or fatal to eat. This last consideration is important in cases where the fish will later be released to the wild, where fishermen might catch it.

In addition, the specific responses of fish to an anesthetic may be important, and the stages of anesthesia can vary with the anesthetic. As mentioned above, quinaldine generally cannot be used to induce the sedation stage, and some chemicals are much more repellent to fish than others. Other anesthetics may initially cause an increase in activity.

Several anesthetics have low solubility in water and must first be mixed with a carrier such as acetone or alcohol to increase their solubility. The need to premix may be inconvenient, particularly in field work. Finally, cost must be considered, especially when large field collections are concerned.

9.14.3 Application of Anesthetics

Rapid immobilization. If an anesthetic is administered in high enough dosages, fish may be immobilized rapidly for capture or handling. The fish is then removed to untreated water for recovery. The chemical may be sprayed in the vicinity of the fish or added to a container holding the fish, or the fish may be removed to a separate bath, depending on the circumstances. Several anesthetics that are unsuitable for sustained anesthesia are satisfactory for rapid immobilization, provided the exposure is of short duration.

Sustained Anesthesia. Under suitable conditions, fish can be sustained safely under anesthesia for several

Table 9-2
Levels of Anesthesia
for Fish

Stage	Description	Behavior
0	Unanesthetized	Normal for the species.
1	Sedatian	Decreased reaction to visual stimuli and/or tapping on the tank; opercular rate reduced; locomotor activity reduced; color usually darker.
2	Partial loss of equilibrium	Fish has difficulty remaining in normal swimming positian; apercular rate usually higher; swimming disrupted.
3	Tatal loss of equilibrium	Plane 1—Fish usually on side or back; can still prapel itself; responds to tap on tank or other vibrations; opercular rate rapid. Plane 2—Locomotion ceases; fins may still mave but ineffectively; responds to squeeze of peduncle or tail; apercular rate decreased.
4	Loss of reflex	Does not respand to peduncle squeeze; opercular rate slaw—often may be erratic. This is the surgical level.
5	Respiratory collapse	Operculum ceases to move; cardiac arrest (death) will accur within one ta several minutes unless fish revived in untreated water.

Source: NOAA (1979)

days. Choosing the proper anesthetic with regard to toxicity and stability is critical. Before the anesthetic is administered, the fish should be starved for 24 to 48 hours to prevent regurgitation of food.

To perform surgery on captured fish, it is simplest to anesthetize the fish to the surgical level; the fish should then be placed in a trough or other restraining device, and its head should be immersed in an anesthetic bath for the duration of the procedure. For longer term surgery, more sophisticated procedures are required. One successful system employs two water baths, one containing untreated water and the other the anesthetic solution. The level of anesthesia can be controlled carefully by selectively recirculating water from the baths over the fish's gills. Steps should be taken to maintain the oxygen content near the saturation level and the ammonia concentration at the minimal level. Filtration may be required to maintain water quality (Klontz and Smith 1968).

Recovery. To revive fish in deep anesthesia, it may be necessary to move them gently to and fro in their normal swimming position. It is helpful to direct a gentle stream of water toward the fish's mouth, which provides a low-velocity current over the gills. It is not advisable to use a strong current or to insert a hose directly into the mouth because this may cause, rather than alleviate, hypoxia. The water in which the fish is being revived must be of good quality.

Some species recovering from certain anesthetics may undergo violent, uncontrolled swimming movements, and steps must be taken in such a situation to prevent self-inflicted injuries. For example, this is usually the case when the yellowtail *Seriola dorsalia* recovers from quinaldine anesthesia. Various physiological changes, some of which may persist for more than a week, have been observed in fish after anesthesia (Houston et al. 1971). During this post-treatment period, additional stress may result in mortality and should therefore be minimized.

NOTE

Anesthetics administered to food fish must be approved by the Food and Drug Administration, and those using anesthetics are advised to be thoroughly familiar with all pertinent regulations. Violations of these regulations carry severe penalties.

Tidepools and Ponds. Anesthetics are useful when collecting fish in tidepools. The water volume in the pool must first be estimated, and then the desired dose of anesthetic is calculated and added to the pool. As the fish become immobilized, they are removed to untreated water as quickly as possible. It is desirable to collect fish from tidepools as the tide is rising, because a moderate amount of surge in the pool helps to flush anesthetized fish out of crevices, and diluting the pool water with incoming water will prevent the killing of specimens that are not going to be collected. With the proper anesthetic and dose, the mortality of uncollected specimens can be reduced to a negligible level (Gibson 1967, Moring 1970).

Reef and Shore. Many species of reef and shore fish can be collected with anesthetics. Quinaldine (10-20%) is used widely for this purpose. One-half to 1.05 quart (0.5 to 1 L) of the solution is generally used for each collection. Species susceptibility is highly variable. For example, angelfish and butterflyfish are highly susceptible, squirrelfish are moderately susceptible, and moray eels are highly resistant. The effectiveness of the anesthetic also varies with the physical situation as well as the skill and experience of the collector. Most anesthetics are at least somewhat repellent, and the fish usually need to be in a situation, e.g., in small caves, short crevices, or under rocks, where they can be confined within the anesthetic's influence for several seconds. The anesthetic is usually dispensed from a squeeze bottle in sufficient quantity to immobilize or partially immobilize specimens on the first application. The fish can then be collected with a hand net or, in the case of small specimens, with a manual "slurp" gun (Figure 9-43).

Figure 9-43
Slurp Gun Used
to Collect Small Fish

Photo © National Geographic Society

A power syringe is available that allows oral anesthetics to be delivered through a probe. This device permits the diver to deliver the anesthetic at closer range to more species of fish than can be done using a squeeze bottle, and this delivery system may make the more expensive anesthetics practical to use for collecting.

Sedentary specimens can sometimes be collected by slowly trickling a light anesthetic dose downstream toward them. Fish in burrows are often difficult to collect with anesthetics because the burrows are so deep that the fish cannot be reached by discharging anesthetic from a squeeze bottle. Attaching tubing, such as a piece of aquarium air line, to the bottle may provide an adequate extension to reach into the burrow. The anesthetic should have repellent qualities that will cause the fish to emerge, because otherwise the fish might become anesthetized in the burrow and remain out of range. A noxious chemical can be added to some non-repellent anesthetics to ensure that the fish emerges.

Scientists at the Scripps Aquarium have developed a successful system for collecting garden eels of the *Taenioconger* species, which were previously difficult to collect. A piece of clear plastic, 6.6 feet (2 m) square, is placed over the area of the eels' burrows and weighted down along the edges with sand. Approximately 1.05 quart (1 L) of 13 percent quinaldine solution in ethanol is applied under the plastic. The area is then left undisturbed for 20 minutes, after which the sedated and immobilized eels are gathered gently by hand. A single collection in a well-developed colony may yield more than 20 eels. This technique can be applied to other burrowing species, although the dosage and time of exposure may have to be varied.

Fish can also be anesthetized by injection. Although earlier attempts at collecting fish with projectile-mounted syringes were limited in their success, a recently developed technique utilizing Saffan®, a veterinary anesthetic, administered by a laser-sighted underwater dart gun, shows much promise. Harvey, Denney, Marliave, and Bruecker (1986) have successfully immobilized small sharks and ratfish with this technique, while Harvey (1986) has used it to collect moray eels and jacks.

Coral heads. It usually is advantageous to enclose coral heads with a loose-fitting net before applying the anesthetic. Some species of fish such as wrasse and hawkfish reside in coral at night and can be collected easily at that time with the aid of anesthetics.

Large-scale collections. One technique used to collect fish over a large portion of a reef is to enclose the desired area with a seine and to administer a large enough quantity of anesthetic to immobilize the enclosed population rapidly. Divers should work as a team to recover the fish because of the danger of the divers becoming entangled in the net. Procedures to free entangled divers should be planned in advance.

Handling large fish. Sharks or other large fish captured by hook may be immobilized by spraying a strong anesthetic solution directly over their gills before bringing them aboard. Gilbert and Wood (1957) used a 1000-ppm tricaine solution successfully in this situation.

Transportation. Anesthetics have been used, with conflicting results, to immobilize fish during transit. The effectiveness of this approach depends on a number of factors, including the type of anesthetic, species of fish, temperature, time in transit, preconditioning of fish, and water quality. Since most fish can be transported successfully without the use of anesthetics, information on the appropriateness of using anesthetics during transit should be obtained from the literature or by experimentation before attempting the procedure.

Summary. The use of anesthetics as collecting agents for aquarium fish is controversial, primarily because of concern about the delayed toxicity of the anesthetic agents. A survey of the literature indicates that, in the majority of species experimentally subjected to repeated anesthetization, delayed mortality is negligible. Professional aquarists at Scripps Aquarium, Steinhart Aquarium, and other institutions have also demonstrated that many other species that have not yet been subjected to formal experimentation can be collected safely and handled without significant mortality.

Most aquatic biologists concerned with collecting agree that judiciously applied anesthetics are useful collecting agents. However, the misuse of these chemicals, especially if widespread, can be very harmful. For example, the practice of using sodium cyanide to collect aquarium fish, which is sometimes done in underdeveloped countries, is ill-advised and has resulted in human deaths, as well as high mortality among the fish and other organisms in the vicinity.

Recommendations. Tricaine® (MS-222) is a highly soluble and virtually odorless powder that is easy to use. It has proved to be a successful anesthetic in a wide variety of applications under a broad range of conditions in both fresh water and seawater, and there is an extensive literature on its properties and use. Tricaine® is a good choice where sustained sedation or surgical-level anesthesia is required, but high cost generally precludes its use as a collecting agent.

Quinaldine has been used widely to collect or handle fish. It is of low solubility in water and is generally dissolved in acetone, ethyl alcohol, or isopropyl alcohol before use in water. Quinaldine is not useful where sedation-level anesthesia is the goal, and it should not be used for major surgery or other painful procedures because it is a poor pain killer. Liquid quinaldine can be converted readily to a water-soluble salt, which greatly facilitates its use. When a mixture of the salt and tricaine is prepared in proper proportions, it combines the desirable properties of both chemicals and is effective at lower doses than either alone. Propoxate® and its analog Etomidate® are two relatively new and highly potent fish anesthetics that have potential as anesthetics for fish collection. Table 9-3 shows the commonly used fish anesthetics, including their recommended dosages.

9.14.4 Diver-Operated Devices

The capture of live fish poses no special problems for divers. Some fish are territorial and maintain discrete regions, while others live in schools and roam widely. Diurnal variations may also cause the fish to change their habitats during a 24-hour period.

Conventional methods of capture such as seining, trawling, and long-lining are not appropriate for capturing fish around coral reefs, and a number of special techniques must be used instead. An array of suction devices called slurp guns has been on the market for some time. These are powered either by rubber tubing, springs, or other means. After cornering a fish, the diver using a slurp gun (Figure 9-43) pulls the trigger, drawing the plunger back and sucking a large volume of water in through a small opening and thus pulling small fish (1-3 inches (2.54-7.6 cm)) into the gun. The fish are then moved into a holding container, and the gun is readied for another shot. The disadvantages of slurp guns are: the small size of the fish that can be captured, the necessity for the diver to be very close to the fish, and the need to corner the fish, usually in a hole, to capture it.

Glass or plastic bottles also may be used to entrap small fish; however, fish may react to the pressure wave created by the moving jar and swim away. All bottles must be flooded fully with water before being submerged. A better technique than the bottle is the use of a piece of plastic core liner or plastic tube with a screen across one end, which can be slipped over fish more easily. Divers on the bottom can also use small gill nets. Animals such as sea urchins may be broken up and placed near the net to attract fish, or divers may herd fish into the net. Once entangled, fish may be withdrawn and placed in bags or wire cages.

As discussed earlier, fish traps may also be effective if baited appropriately and placed at a proper point either on the bottom or in the water column. Divers can then remove fish from the trap and rebait it while it remains on the bottom.

Deepwater fish can be caught on hook and line and reeled to 60 to 100 feet (18.3 to 30.1 m), where divers can insert hypodermic needles into those with swim bladders and then decompress the fish. There is an 80 percent recovery rate on many species of rock fish when this technique is used. A dip net fastened to the end of a pole spear is useful in collecting fish near the bottom. The fish may be pinned against a rock or sand bottom, taken out of the net, and placed in an appropriate container; again, needle decompression may be helpful.

Many larger fish such as rays, skates, or harmless sharks may be caught either by hand or by a loop of heavy monofilament line on the end of a pole (such as a snake stick). Electric fish and rays should not be taken with metal poles or rods because of the shock potential (see Section 12.4).

Invertebrates may be collected by divers wearing gloves. A pry bar, screwdriver, putty knife, or diving

Table 9-3
Fish Anesthetics

Anesthetic	Qualities	Dosage (varies with species, temperature, etc.)	Common Use	Remarks	References
Benzocaine®	Powder, soluble in ethanol	25-100 mg/L	Immobilization, deep anesthesia	Widely used in human medicine; safe and effective with fish.	Caldarelli 1986
Chloral hydrate	Solid, soluble, inexpensive	1-4 g/L	Sedation	Low potency; not widely used.	McFarland 1959 McFarland 1960 Bell 1967
Cresols	Liquid; mix 50:50 with acetone to facilitate solution.	20-40 mg/L for immobilization	Collection	Cresols have undesirable toxic effects; para-cresol is the most effective isomer.	Howland 1969
Etomidate®	Make 1 percent solution in propylene glycol.	2-10 mg/L	Immobilization	High potency; analog of Propoxate®; longer sedation times and safer than quinaldine and MS-222 mixture.	Amend et al. 1982 Limsowan et al. 1983
Methylpentynol (Oblivon®, Dormison®)	Liquid, moderately soluble	0.5-2 ml/L 1500-8000 mg/L	Sedation or deep anesthesia	Widely used but less desirable than other anesthetics; low potency.	Bell 1967 Klontz and Smith 1968 Howland and Schoettger 1969
Phenoxyethanol (2-phenoxyethanol)	Oily liquid	0.1-1 ml/L	Immobilization	Used frequently with salmonids.	Klontz and Smith 1968 Bell 1967
Propoxate® (McNeil R7464)	Crystalline; soluble	1-4 mg/L	Collection, immobilization	Good collecting agent.	Thienpoint and Niemegeers 1965 Howland 1969
Quinaldine (Practical grade)	Oily liquid, soluble with difficulty; dissolve in 10-50 percent acetone, ethanol, or isopropyl alcohol to facilitate solution.	5-70 ml/L	Widely used for collection, immobilization	No sedation state; poor analgesic; efficacy varies widely with species and water characteristics; long exposures toxic.	Schoettger and Julin 1969 Locke 1969 Moring 1970 Gibson 1967 Howland 1969

Table 9-3
(Continued)

Anesthetic	Qualities	Dosage (varies with species, temperature, etc.)	Common Use	Remarks	References
Quinaldine sulfate ($QdSO_4$)	Crystalline solid	15-70 mg/L	Collection, immobilization	Prepared from liquid quinaldine and has same properties.	Allen and Sills 1973 Gilderhus, Berger, Sills, Harman 1973a
Rotenone®	Powder or emulsion	0.5 ppm	Ichthyocide; occasionally used for collecting	Used to salvage fish from freshwater ponds. Limited use in seawater for live collecting.	Tate, Moen, Severson 1965
Sodium cyanide	Solid	DO NOT USE	Used in Philippines and elsewhere for collecting	Dangerous to humans; causes high mortality in fish.	
Styrylpyridine (4-styrylpyridine)	White powder; soluble	20-50 mg/L	Immobilization, deep anesthesia	Not widely used but a successful anesthetic.	Klontz and Smith 1968
Tricaine® (MS-222, tricaine methanesulfonate)	White crystalline powder; readily soluble	15-40 mg/L for sedation 40-100 mg/L for deep anesthesia 100-1000 mg/L for rapid immobilization	Immobilization, deep anesthesia; most widely used anesthetic	Expense bars its use for collecting; used extensively in surgery, fish handling, transport.	Klontz and Smith 1968 Bell 1967
Urethane	Carcinogenic	DO NOT USE	Immobilization, deep anesthesia	Carcinogenic.	Wood 1956
Mixtures of MS-222 and $QdSO_4$	Powder, readily soluble	Various, e.g., 10:20 ppm $QdSO_4$: MS-222 equals 25 ppm $QdSO_4$ or 80-100 ppm MS-222	Immobilization, deep anesthesia	Combines desirable properties of each anesthetic; combination can be used in lower concentration than either anesthetic alone.	Gilderhus, Berger, Sills, Harman 1973b

Source: Donald Wilkie

knife may be useful in removing some specimens from their substrate. Delicate animals such as nudibranches may be placed in separate plastic jars, vials, or ziplock bags. Vials and jars should be open at the beginning of the dive but be completely filled with water before being returned to the surface.

Traps are effective for crabs, lobsters, and, occasionally, octopus. Nylon net bags are more easily used for collecting than bottles or plastic bags. Animals that are neutrally buoyant will float out of the bottle or plastic bag when it is reopened to add another specimen.

Animals that live in the upper few centimeters of sediment or sandy bottom may be sampled by using either a scoop, which has a line inscribed showing a given volume, or a cylinder made of plastic, stainless, aluminum, or other material that can be forced into the soft substrate. A simple cake server or spatula can be inserted from the side to provide a closure as the core of sediment is withdrawn from the bottom. The diameter of the cylinder should be such that it fits snugly over the mouth of the collecting bottle so the material can be forced into a labeled jar.

Nylon or other plastic screens can be obtained in a variety of mesh sizes. These may be tied over ends of plastic tubes as a sieve or be sewn into a bag to be used to hold sediment samples.

SECTION 10
DIVING UNDER SPECIAL CONDITIONS

DIVING UNDER SPECIAL CONDITIONS 10

10.0 GENERAL

The characteristics of underwater environments, such as temperature, visibility, and type of marine life, vary significantly from geographic region to region and influence the amount and type of diving work that can be carried out under water. The following paragraphs describe the diving conditions most typical of U.S. coastal and other areas and provide an overview of the diving characteristics of these regions.

WARNING

When Diving in an Unfamiliar Region, Information About Local Conditions Should Be Obtained From Divers Who Are Familiar With Local Waters. A Checkout Dive Should Be Made With a Diver Familiar With the Area

10.1 GEOGRAPHIC REGIONS

For purposes of discussion, the coastal regions are classified as shown on the following table. The principal characteristics of each region are described in the following sections of this chapter.

Region	Area Encompassed
Northeast Coast	Maine to Rhode Island
Mid-Atlantic Coast	Rhode Island to Cape Hatteras
Southeast Coast	Cape Hatteras to Florida
Gulf of Mexico Coast	West Coast of Florida to Texas
Northwest Coast	Subarctic Alaska to Oregon
Mid-Pacific Coast	Northern and Central California
Southwest Coast	Point Conception to the Northern Baja Peninsula
Central Pacific Ocean	Hawaiian and Leeward Islands
Polar	Arctic and Antarctic
Tropics	Caribbean and Florida Keys

10.1.1 Northeast Coast

Diving in northeastern waters is an exciting and chilling experience. Generally, the best diving conditions in terms of water temperature, sea state, and underwater visibility occur from June through October. As one progresses north along the New England coast, water temperature decreases and underwater visibility increases.

Water temperatures near the surface during the spring and summer, when a substantial thermocline exists, range from 50 to 70°F (10 to 21°C). Temperatures at 100 feet (30.5 m) range from 48 to 54°F (9 to 12°C). During the winter months, the temperature of the water column is essentially homogeneous, with temperatures reaching as low as 28.5°F (-2°C). Subzero air temperatures and strong winds cause wind chill factors as low as -70 to -80°F (-57 to -62°C). Wet suits and variable-volume dry suits have become standard for winter diving in the Northeast (see Section 5.4).

Underwater visibility is primarily a function of sea state and vertical turbulence in the water column. In the Northeast, horizontal visibility of 50 to 80 feet (15 to 24.4 m) may occur occasionally throughout the year, usually in connection with calm seas. Proximity to a land mass or to estuaries or harbors is associated with a decrease in visibility because the load of suspended material in the runoff from the land mass and the processes associated with the mixing of fresh and salt water greatly elevate turbidity. During the summer, biologically caused 'red tide' conditions may occur, lowering visibility to less than 1 foot (0.3 m). Coastal waters within the Gulf of Maine have an average range in visibility of 25 to 35 feet (7.6 to 10.7 m), while visibility in waters south of Cape Cod averages 10 to 15 feet (3.0 to 4.6 m).

Several species of brown algae comprise the large kelp of the New England coast. Unlike the kelp of California, these kelp do not form surface canopies (see Section 10.11). New England kelp occasionally extend as much as 25 feet (7.6 m) off the hard ocean bottom and, although they look impenetrable, they do not in fact present a significant entanglement hazard. Generally, these algal plants are sparsely distributed and seldom project more than 6 to 8 feet (1.8 to 2.4 m) from the bottom.

Currents along the New England coast are primarily tidal in origin and generally do not exceed 0.5 knot (0.25 m/s). Faster currents may be encountered in channels and in river mouths. Divers should be cautious in the waters off the New England coast, especially when diving in strong currents and cold water, because of the potential for overexertion. The surf in this region is modest compared with the surf in California, but it is especially hazardous along rocky, precipitous coastlines such as the coast of Maine. Short-period waves as high as 5 to 10 feet (1.5 to 3.0 m) can create very rough and turbulent sea states along these coasts and can push divers into barnacle-covered rocks.

Hazardous marine animals. Relatively few species of fish and invertebrates in the waters off the New England coast are potentially harmful to divers. Sharks of several species are occasionally seen, but they are generally not harmful to divers (see Section 12.3.1). These are the mako, dusky, tiger, great white, hammerhead, and blue shark; occasionally, the filter-feeding basking shark is mistakenly identified as a dangerous shark. The torpedo ray (electric ray) (see Figure 12-19), cow-nosed ray, and stingray are found off southern New England (Cape Cod and south). Documented diver-shark or diver-ray encounters are relatively rare along the New England coast.

The most bothersome fish in this region is the goosefish, which may weigh as much as 50 pounds (23 kg) and grow to 4 feet (1.2 m) in total length. It is the habit of the goosefish to lie partially buried on the ocean floor waiting for unsuspecting 'meals' to pass by. This fish is approximately one-half head and mouth and one-half tail. The sight of a goosefish is enough to startle even a seasoned diver, but these fish do not generally attack unless they are provoked. The wolffish is another bottom-oriented creature that is highly respected by fishermen and divers for its strength and aggressiveness when bothered. The wolffish's six large canine tusks are capable of inflicting considerable damage, as many fishermen have discovered when trying to boat this species.

The green sea urchin, which has many stout spines that can easily puncture a rubber wet suit, can also injure divers. Unless the tip of the urchin's spine is surgically removed from the diver's flesh, it will cause a painful 'lump' under the skin that may last for months or years. The green sea urchin is found in very dense concentrations on hard substrates to depths of 50 to 60 feet (15.2 to 18.3 m).

10.1.2 Mid-Atlantic Coast

Waters off the coasts of the mid-Atlantic states are characterized by low visibility and cold bottom temperatures. Bottom topography generally consists of flat sand clay or gravel and occasional low-relief rocky outcroppings. Wrecks are found frequently off the New York-New Jersey coasts and off Cape Hatteras.

Water temperatures on the surface range during the summer months from 72-75°F (22-24°C) and from 40-60°F (4-16°C) on the bottom, depending on depth, proximity to the shore, and general location. In the mid-Atlantic Bight (Montauk Point, N.Y. to Cape May, N.J.), a large bottom 'pool' of cold winter water is trapped every summer. This pool or cell contains the coldest summer water on the entire eastern continental shelf. Tidal and wind movement of cold bottom water can cause a significant and sudden change in the bottom temperature of the water off the New Jersey coast.

A chief characteristic of the mid-Atlantic water column in the summer is the thermocline. The rapid decrease in temperature at the thermocline may cause an unsuspecting and unprepared diver enough discomfort to abort the dive. Plankton gathered at the thermocline also can decrease the light so drastically that artificial lights occasionally are needed in water depths beyond 70 feet (21.3 m). In the Cape Hatteras area, eddies from the Gulf Stream often bring warm clear water to the coast. Bottom temperatures are warmest in October and early November after the cold bottom water mixes with the warmer upper layers. Winter temperatures in the northern range drop as low as 35°F (2°C) near shore and are relatively homogeneous throughout the water column, with slightly warmer temperatures on the bottom.

Underwater visibility is best during September-October, when it is common to be able to see for distances of up to 60 feet (18.3 m). Many of the inshore waters of the northern area and the waters near the major estuaries, such as the Hudson and Chesapeake, have poor visibility throughout most of the year. Visibility can range from 0 to 15 feet (4.6 m) in these areas, but improves with distance offshore. Tides may cause large changes in visibility for as much as 3 miles (4.8 km) offshore near bays and rivers.

Tides and currents. Strong tidal currents can be expected in the Chesapeake Bay, parts of the New York Bight, off the outer banks of North Carolina, and in Long Island Sound. Diving in these areas can be especially hazardous if the diver becomes lost because of low visibility and is swept away from the planned exit area.

Waves. Long-period open ocean waves in the mid-Atlantic are generally not hazardous to divers, although summer squalls can cause quick 'chops' that may be a problem. Waves pose the greatest danger to divers attempting to dive off the end of a rock jetty in a moderate to heavy surf; divers too close to the end of a jetty can be picked up and thrown into the rocks by a wave. The surf in these waters is generally moderate, and most beaches are composed of sand rather than rock, which makes entry from the shore relatively easy for divers.

Although sharks are numerous off the coasts of the mid-Atlantic states, there have been few diver-shark encounters. However, divers carrying speared fish have been molested by sharks, and divers are therefore advised to carry fish on a long line, especially in murky water.

As in the Northeast, the goosefish is probably the area's most troublesome marine creature for divers. Divers swimming close to the bottom to see their way in murky water often inadvertently place a hand or foot in the mouth of a goosefish lying camouflaged on the bottom and thus run the risk of being bitten. Stinging jellyfish are so abundant in estuaries, especially during the summers in the Chesapeake Bay, that maximum protection against them is necessary.

10.1.3 Southeast Coast

For the most part, the waters off the coasts of the southeastern states are tropical. Warm temperatures prevail and can reach as high as 75 to 80°F (24 to 27°C) during the summer months. In the most northern portions of this region of Georgia, South Carolina, and southern North Carolina, less tropical conditions prevail. Water temperature during the summer in this area is about 70°F (21°C). In the area just south of Cape Hatteras, the Gulf Stream passes close to land, causing the water temperature to be warmer near shore than it is to the south. During the winter, water temperature in the southernmost areas remains 65 to 70°F (18 to 21°C); in the more northerly waters, however, temperatures drop as low as 50°F (10°C). In the tropical and subtropical waters of the Southeast, there are a vast number of different species of marine animals.

Visibility in southern waters is good to excellent in the offshore areas; closer to shore, however, it drops to 25 to 30 feet (7.6 to 9.1 m), and in harbors and bays, it can be poor. Farther north, both offshore and nearshore visibility drops drastically and averages 20 to 25 feet (6.1 to 7.6 m).

When diving at the boundary of major oceanic current systems such as the Gulf Stream, special care must be exercised because of the episodic turbulent eddies that occasionally spin off the main mass of moving water. Extra precautions also must be taken because of the meandering nature of the current's edge; relatively quiet water near the edge may suddenly change to water with a current velocity of 1 knot or more. Dives in boundary regions must be planned to anticipate high current speeds, and appropriate surface support must be provided. As the diver descends, there are often sharp boundaries between water masses in the water column that have different current velocities. The current generally slows about 1-2 feet (0.3-0.6 m) above the bottom, and if divers hug the bottom contours they can work without interference from the current. However, the tending boat operator must be aware of the current differential and must establish a reference for the diver's position to prevent the boat from being carried away from the dive site. Dropping a well-anchored buoy over the side at the beginning of the dive is a good means of establishing such a reference. Carefully monitoring the bubbles of the diver is extremely important in this type of diving. Some means of diver recall must be established in case the crew on the surface boat loses sight of the diver's position (see Section 14.2.2).

10.1.4 Gulf of Mexico

Water temperature in the Gulf of Mexico drops to a low of about 56°F (13°C) during the winter months and rises to about 86°F (30°C) in the summer. Visibility offshore is generally good to excellent and may even exceed 100 feet (30.1 m) around some reefs. Underwater visibility near shore is poor, particularly in areas near river outfalls, in bays and estuaries, and off some beaches. Occasionally, a mass of clear offshore water may move inshore and increase the near-shore visibility up to 75 feet (22.9 m) in regions southeast of Mobile, Alabama.

Currents in the gulf are generally negligible but should still be of concern to divers. At times, strong currents may occur around offshore oil platforms, and local knowledge must be relied on in this situation. Weather conditions and running seas are unpredictable in the gulf. Unforecasted storms with 6- to 12-foot (1.8 to 3.6 m) seas have curtailed diving operations in this region of the country in the past.

10.1.5 Northwest Coast

Diving activities in the northwest take place off the coast of subarctic Alaska and extend to areas offshore from Oregon. Water temperatures in subarctic Alaska range from 34 to 38°F (1 to 3°C) during the winter months and average 45 to 50°F (7 to 10°C) during the summer. Divers in these waters must give serious consideration to their choice of diving dress so that dive duration is not affected by the cold. During the winter, temperature and wind conditions may combine so that some bays, inlets, and near-shore waters freeze over.

Visibility in Alaskan waters varies drastically from place to place and from time to time. The best visibility occurs along coastlines and in the Aleutians, where it may range, at best, from 40 to 80 feet (12.2 to 24.4 m). Visibility in the waters of bays and straits is usually 15 to 30 feet (4.6 to 9.1 m). At any location, visibility may become temporarily limited by storms or phytoplankton blooms. Late each spring in southeast Alaska, the visibility in the upper 30 to 40 feet (9.1 to 12.2 m) of the water column may be near zero because of phytoplankton, but below that layer the water may be very clear (visibility of 40 feet (12.2 m) or more). Although this deep, clear water is often dark because of the shading effect of the overriding low-visibility water, there is usually sufficient ambient light to work.

Currents and tides are strong and unpredictable in subarctic Alaskan waters. Tides are extremely heavy and can cause currents as high as 10 knots in narrows. Currents also vary significantly and have been observed to change direction within a period of minutes.

Much of the Alaskan coastline is steep and rocky; many areas are too steep to allow divers either to enter or leave the water. Entry and exit points must be carefully selected before a dive. Most sections of coastline are accessible only from boats. During times of heavy seas or swells, many near-shore diving locations become completely unworkable.

Alaskan waters harbor relatively few hazardous marine organisms. Those that cause divers the most trouble are the urchins, barnacles, and jellyfish, with their potential to cause punctures, abrasions, and stings. Dense beds of floating kelp can cause some problems for divers, especially during surface swimming. Sharks and whales are common but are rarely, if ever, seen under water and generally do not influence diving activity in any way. The presence of killer whales, which are common, is an exception to this general rule.

Although no known diver/killer whale encounters have taken place in Alaska, general caution should keep divers out of the water if these animals are known to be near. Steller sea lions are very abundant in some areas of Alaska; although there are no reports that these animals have ever harmed divers in Alaska, California sea lions have been known to injure divers. Because sea lions are large, fast, and agile and are attracted to divers, they can disrupt an otherwise routine dive. In addition to being a psychological distraction, the activity of sea lions often causes serious roiling of bottom sediments and a reduction of visibility.

Farther south, in the waters off Washington and Oregon, water temperatures range from about 43 to 60°F (6 to 16°C) over the year in protected areas such as Puget Sound. In open ocean waters, depending on the water masses moving through, temperatures ranging from 40 to 60°F (4 to 16°C) may be encountered throughout the year. Visibility usually is low, ranging from 5 to 25 feet (1.5 to 7.6 m) in coastal water near beaches and from 0 to 70 feet (0 to 21.3 m) in protected Puget Sound waters.

Currents in certain areas may be strong and unpredictable. This is especially true in river diving, where very low visibility can cause orientation problems. Logs, stumps, wrecked automobiles, fishing hooks and lines, and other bottom trash also pose distinct dangers to divers working in Alaskan rivers (see Section 10.15).

10.1.6 Mid-Pacific Coast

The mid-Pacific coastal region includes the waters of Northern and Central California. From San Francisco north, the best diving conditions in terms of underwater visibility as well as water temperatures generally occur from June through September. From San Francisco south to Point Conception, good diving conditions may continue through December.

From San Francisco north to the Oregon border, summer temperatures generally range from about 48 to 56°F (9 to 13°C). Fall and early winter temperatures vary from 52 to 60°F (11 to 16°C), and late winter and spring temperatures from 45 to 54°F (7 to 13°C). A thermocline generally exists at depths from 20 to 40 feet (6.1 to 12.2 m) during late spring and summer. The difference in surface and bottom temperatures during this period ranges between 2 and 5°F (-17 and -15°C). A full wet suit, including hood, boots, and gloves, is a necessity when diving in these waters.

Underwater visibility varies quite drastically throughout the area from summer to winter. From Fort Bragg to the Oregon border, late spring and summer underwater visibility ranges between 10 and 15 feet (3.0 and 4.6 m). In the late summer and fall, underwater visibility increases to about 15 to 25 feet (4.6 to 7.6 m). During the winter and early spring, visibility decreases to 0 to 10 feet (0 to 3.0 m). South of Fort Bragg down to San Francisco, visibility ranges from 10 to 20 feet (3.0 to 6.1 m), increasing to 30 feet (9.1 m) in the fall. From Santa Cruz north to San Francisco, visibility ranges from 5 to 15 feet (1.5 to 4.6 m) in the early spring and summer, 10 to 25 feet (3.0 to 7.6 m) in late summer and fall, and 0 to 10 feet (0 to 3.0 m) during the winter and early spring. From Point Conception to Santa Cruz, visibility ranges from 15 to 25 feet (4.6 to 7.6 m) during the late spring and summer and from 15 to 50 feet (4.6 to 15.2 m) in the fall and may occasionally reach 100 feet (30.5 m) near Carmel Bay. During winter and early spring, one can expect visibility to extend 5 to 20 feet (1.5 to 6.1 m). The main factors controlling underwater visibility in this area are the huge plankton bloom, which occurs during upwelling in the spring and summer, and the dirty water conditions caused by rough seas and river runoffs during the winter and early spring.

Three species of surface-canopy-forming brown algae—kelp—occur on the Pacific coast. From Monterey north, the dominant kelp is the bull kelp. This particular species forms large beds but, because of its structure, does not pose the same entanglement hazard to divers as the giant kelp (see Section 10.10).

North of Point Conception, surf conditions are probably the most important consideration in planning a dive. Divers can expect 2- to 3-foot (0.6 to 0.9 m) surf in most areas even on calm days, and on rough days it is not uncommon to see waves 10 feet (3.0 m) or more high. Divers should always scout the proposed dive area before going into the water to determine the safest area of entry and, in case conditions change, to choose alternate exit sites (see Section 10.2.1).

Long-shore currents and tidal currents are common and tend to be severe in northern and central California. On very windy days, divers should watch for strong currents around headlands, off rocky shores, and near reefs. Rip currents are very common along beaches and in coves (see Section 10.2.3).

Hazardous marine animals. As in other areas, divers must watch for sea urchins, jellyfish, and rockfish, but shark attacks in this area are not common. In the last 15 to 20 years, fewer than 2 dozen shark attacks involving divers have been recorded; however, diving around the Farallon Islands, Bodega Bay, Tomales Bay, and off San Francisco is not recommended except when underwater visibility is ideal. Stingrays and electric rays are also found in the mid-Pacific coastal region (for appropriate precautions, see Section 12.4).

There are five ecological reserves in this area, where all animals and plants are protected: Point Lobos State Reserve, Point Reyes Seashore area, Salt Point State Park, Estero de Limantour Reserve in Marin County north of San Francisco, and Del Mar Landing in Sonoma County. Divers should consult with the park authorities to determine the boundaries of these marine reserves and the restrictions that apply to them.

10.1.7 Southwest Coast

The waters of the Southwest include the area from Point Conception to the northern Baja Peninsula. Water temperatures range from 50 to 60°F (10 to 16°C) in winter and 55 to 70°F (13 to 21°C) in summer, with some localized areas made colder by upwelling. During much of the year, temperatures at depths below 100 feet (30.5 m) are fairly stable in the 50's and low 60's (10 to 16°C). In fall and winter there is a great deal of mixing in the upper layers and discrete temperature zones do not exist. However, a distinct summer thermocline at 40- to 60-foot (12.2 to 18.3 m) depths causes a sharp temperature drop that should be considered in dive planning.

Horizontal visibility under water ranges from 5 to 10 feet (1.5-3.0 m) along much of the mainland coast to as much as 100 feet (30.5 m) around the offshore islands. The best visibility conditions occur in the late summer and fall. During spring and early summer, underwater visibility is generally less (30-50 feet (9.1-15.2 m)) around the islands, at least in part because of prevailing overcasts and heavy fogs. Winter storm conditions and rain runoff can reduce the visibility to zero for miles along the mainland coast, because the prevailing long-shore current distributes suspended material from storm drains and river mouths.

Shore conditions along the mainland coast of southern California range from sand beaches to high palisade cliffs. Ocean access from these areas is often impossible, and a careful check of charts and maps, supplemented by a preliminary site visit, is highly recommended before initiating a dive. The offshore islands generally are accessible to divers only by boat. Moderate-to-heavy surf prevails along the entire mainland coast and on the windward sides of the offshore islands. Under certain weather conditions, the normally calm leeward sides also may present hazardous diving conditions.

Currents and tides are not of prime importance in the southwest coastal region, although there are local exceptions. Currents around the islands, especially during tidal changes, may attain speeds of 3 to 4 knots (1.5 to 2 m/s). The direction and relative strength of nearshore currents can be observed both topside and under water by watching the degree and direction of kelp layover.

Hazardous marine organisms in this region include: sharks (especially around the offshore islands) such as the blue, horned, swell, angel, and leopard; whales (including killer whales); moray eels; sea urchins; and jellyfish. Divers should be aware of the habitats, appearance, and habits of these species (see Section 12).

Sewer outfalls are common along the mainland coast, and direct contact with sewer effluent should be avoided (see Section 11). The outfall discharge point may occur from a few hundred feet to several miles offshore, in from 60 to several hundred feet (18.3 to several hundred meters) of water. The effluent sometimes rises to the surface in a boil characterized by elevated temperatures, paper and other debris, and an unpleasant odor. If diving must be conducted in outfall areas, precautions such as immunization, use of full-face gear, and scrupulous post-dive hygiene must be observed (see Section 11 for polluted-water diving procedures). Most outfall discharge points are marked on charts and can be identified on the surface by a boil or by an orange-and-white striped spar buoy anchored near the pipe terminus.

As in Northern California, ecological reserves that have various restrictions have been established in the southwestern coastal region. The local office of the California Department of Fish and Game is the best source of information about the location of these reserves and any restrictions that pertain to them.

Diving in northern Mexican (upper Baja California) waters is similar to that in lower southern California. However, Mexico imposes heavy fines and impounds the boats of people diving in Mexican waters without proper permits; permits can be obtained through the Mexican government or from Mexican customs officials in San Diego.

10.1.8 Central Pacific Ocean

The most accessible diving in this area is around the Hawaiian Archipelago, which consists of the major Hawaiian Islands and the lesser known Leeward Islands. The major islands are: Hawaii, Maui, Kahoolawe, Lanai, Molokai, Oahu, Kauai, and Niihau. The Leeward Islands are a group of rocks, shoals, and islets that are remnants of ancient islands and seamounts that extend from Kauai to Midway Island. They are all wildlife reserves and generally are inaccessible except to government personnel or authorized visitors.

The average water temperature around the major islands is 76°F (24°C) and changes very little with the seasons. Underwater visibility is almost always excellent, ranging from 50 to 100 feet (15.2 to 30.5 m) or more. Currents can sometimes be a problem in channels and near points and may reach speeds of up to 3 knots (1.5 m/s). High surf is also a potential hazard and may vary widely with the seasons.

It is possible to make shore entries from all the islands, but rocks, surge, and surf must always be considered when planning entries and exits (see Section 10.2.1). Since drop-offs occur very near shore and continue for several hundred feet, it is easy to get into deep water quickly after making a shore entry. Caution must always be exercised when making repetitive dives.

Although most forms of dangerous marine life can be found in Hawaiian waters, they are uncommon. There have been a few recorded shark attacks over the years, but they are extremely rare and usually involve swimmers or surfers. Eel bites, sea urchin punctures, and coral abrasions are the most common types of injury. No license is needed to harvest fish or crustaceans for home consumption; however, game laws in most states place season and size limitations on some species.

10.1.9 Arctic and Antarctic

The two most important factors to be considered in arctic and antarctic environments are the effects of cold on the diver and the restricted access to the surface when diving under ice. These topics are covered in detail in the sections dealing with diving in cold water (Section 10.8) and diving under ice (Section 10.9).

Temperature in arctic waters can be as low as 28°F (-2°C), but the air temperature and its associated chill factor may be more limiting to divers than the cold water itself. Often, surface temperatures as low as -40 to -50°F (-40 to -46°C) are reached, with accompanying wind velocities that bring the chill factor to a temperature equivalent to -100°F (-73°C) or less. In such conditions, protecting divers from the extreme cold is paramount both before and after the dive, although the problem is greater after the dive because the diver is then both wet and chilled. When diving is being conducted under the ice, the dive should begin and end in a heated shelter positioned over the entry hole. If such a shelter cannot be positioned over the hole, one should be located within a few steps of the entry point. The heated interior of an airplane parked nearby may satisfy this requirement. When exposed to extremely low air temperatures for longer than a few minutes, divers should wear heavy, loose-fitting hooded parkas. Gloves (in the case of dry suits) or entire wet suits can be flooded with warm water to forestall the chilling effects of air and to provide greater initial comfort in the water. Hot water can be carried in insulated containers such as thermos jugs.

In polar regions the marine species of concern are seals, walrus, killer whales, and polar bears. A predive reconnaissance by an experienced observer will indicate if any of these animals is in the vicinity or is likely to cause a problem (see Section 12.5).

10.1.10 Tropics

Tropical waters provide the most interesting environment for diving, because underwater visibility is usually excellent and marine life abounds. The visibility in tropical waters is generally 50 feet (15.2 m) or more. There is little variation throughout the year, although the waters may become murky and silty after a storm, during plankton blooms, or from silting near shore. Water temperatures hover around 70°F (21°C) during the winter months and may be as high as 82°F (28°C) in shallower waters during the summer.

Marine life is abundant, and some forms are dangerous to divers. Sharks thrive in these waters and precautions should be taken when they are sighted. A wide variety of poisonous marine animals (jellyfish, scorpionfish, sea snakes) also abounds (see Section 12).

10.1.11 Diving in Marine Sanctuaries or Underwater Parks

Divers may on occasion dive for recreation or work in sanctuaries or underwater parks. These marine sanctuaries have been set aside for the purpose of preserving or restoring recreational, ecological, or esthetic values. Examples include the Key Largo National Marine Sanctuary, Biscayne National Park, John Pennekamp Coral Reef State Park in Florida, and Buck Island in the Virgin Islands National Park.

Marine sanctuaries are built around distinctive marine resources whose protection and proper use require comprehensive, geographically oriented planning and management but do not necessarily exclude use by people. It is important when diving in these areas to follow the rules and regulations established for sanctuary management. Accordingly, when conducting working or scientific dives in designated marine sanctuaries and parks, it is important to check with local authorities before beginning operations.

10.2 DIVING FROM SHORE

A diver should expect to encounter a wide variety of conditions when entering the water from shore. Shorelines vary greatly, and diving from a particular shore requires individual preparation and planning.

Before entering the water from shore, special attention should be given to the predive equipment checkout. Since diving equipment is often placed on the ground near the water, small dirt particles may have entered a space in the equipment that requires a perfect seal or has a close tolerance. Even the smallest amount of dirt in a regulator or reserve valve may cause a serious air leak or a valve malfunction. Extra care must be taken to ensure that diving equipment is kept as free from dirt as possible.

If the dive from shore is to be made to a precise underwater location, it is advisable to mark the spot clearly at the water surface. This can be done by using a marker buoy or surface float. A small marker buoy floating on the surface, however, may be difficult for a diver to see; therefore, compass bearings, underwater contours or features, or triangulation methods using known shore positions should be used initially in locating a dive site.

When commercial diving operations are being conducted from shore without a boat, OSHA regulations require that the international code flag alpha be displayed at the dive location. If entry conditions permit, divers should carry and/or tow the flag with them during the dive (see Section 14.2.4). It is also advisable to equip each diver with a day/night signal flare for signaling the shore in an emergency. These flares provide a quick means of accurately locating a diver on the surface (see Section 5.6.8).

Entering the water from a smooth, unobstructed shoreline where the water is relatively quiet poses no problem. Most lakes, rivers (where currents near shore are not swift), bays, lagoons, quarries, and ocean coastlines (where surf is negligible) have shorelines of this type.

10.2.1 Through Surf

Entering the water even through moderate surf when burdened with diving equipment is a difficult and potentially hazardous operation. A careful analysis of surf conditions should be made and, if conditions are considered too severe to allow safe passage to open water, the dive should be terminated.

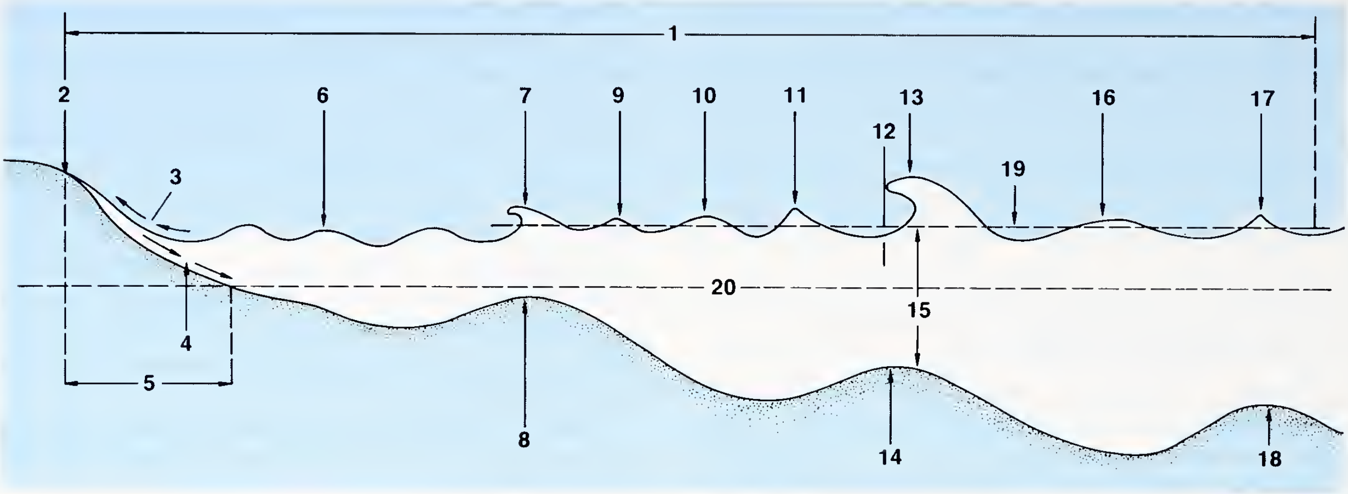
WARNING

Before Diving Through Surf From an Unfamiliar Beach, Local Divers Should Be Consulted About Local Conditions

Before entering the water, divers should observe the surf. Waves traverse vast expanses of ocean as swell, with little modification or loss of energy. However, as the waves enter shallow water, the motion of the water particles beneath the surface is altered. When a wave enters water of a depth equal to or less than one-half of its wavelength, it is said to "feel bottom." The circular orbital motion of the water particles becomes elliptical, flattening with depth. Along the bottom, the particles oscillate in a straight line parallel to the direction of wave travel.

As the wave feels bottom, its wavelength decreases and its steepness increases. As the wave crest moves into water whose depth is approximately twice that of the wave height, the crest changes from rounded to a higher, more pointed mass of water. The orbital velocity of the water particles at the crest increases with

Figure 10-1
Schematic Diagram of Waves
in the Breaker Zone



A diver standing on the shore and looking seaward would observe and note: (1) Surf zone; (2) limit of uprush; (3) uprush; (4) backrush; (5) beach face; (6) inner translatory waves; (7) inner line of breakers; (8) inner bar; (9) peaked-up wave; (10) reformed oscillatory wave; (11) outer translatory waves; (12) plunge point; (13) outer line of breakers; (14) outer bar (inner at low tide); (15) breaker depth, 1.3 × breaker height; (16) waves flatten again; (17) waves peak up but do not break on this bar at high tide; (18) deep bar (outer bar at low tide); (19) still-water level; and (20) mean low water.

Adapted from US Army Corps of Engineers (1984)

increasing wave height. This sequence of changes is the prelude to the breaking of the wave. Finally, at a depth of approximately 1.3 times the wave height, when the steepest surface of the wave inclines more than 60 degrees from the horizontal, the wave becomes unstable and the top portion plunges forward. The wave has broken; this turbulent form is called *surf* (Figure 10-1). This area of "white water," where the waves finally give up their energy and where systematic water motion gives way to violent turbulence, is called the *surf zone*. The surf's white water is a mass of water containing bubbles of entrapped air; these bubbles reduce the normal buoyancy of the water. Having broken into a mass of turbulent foam, the wave continues landward under its own momentum. Finally, at the beach face, this momentum carries it into an uprush or swash. At the uppermost limit, the wave's energy has diminished. The water transported landward in the uprush must now return seaward as backwash, i.e., as current flowing back to the sea. This seaward movement of water is generally not evident beyond the surface zone or a depth of 2-3 feet (0.6-0.9 m).

By watching the surf for a short period of time, water entry can be timed to coincide with a small set of waves. When ready to enter, the diver should approach the water, fully dressed for diving. At the water's edge, the diver should spit on the faceplate, rinse and adjust it to the face, and place the snorkel in the mouth. With one hand on the faceplate, the diver should then turn around and back into the water with knees slightly bent and body leaning back into the wave. If conditions are good, the diver should begin swimming seaward on the surface, using a snorkel. If heavy sets of waves are encountered, it may be necessary to switch to scuba and to swim as close to the bottom as possible. If the bottom is rocky, divers can pull themselves along by grasping the rocks; on a sandy bottom, a diver can thrust a knife into the bottom to achieve the same purpose. Ripples on a sandy bottom generally run parallel or somewhat obliquely to shore, and they can be used to navigate through the surf zone by swimming perpendicular to them. Divers entering with a float should pull it behind them on 10 to 30 feet (3.0 to 9.1 m) of line and should be aware of the possibility that turbulence may cause the line to wrap around a leg, arm, or equipment.

WARNING

Divers Near the Surface Should Not Hold Their Breath When a Wave Is Passing Overhead Because the Rapid Pressure Drop at the Diver's Depth When the Wave Trough Passes Overhead May Be Sufficient to Cause a Lung Overpressure Accident

Swimming over breakers should not be attempted. As breakers approach, the diver should duck the head and dive under and through them. Diving at the base of the wave is advantageous because the water molecules will carry the diver up behind the wave.

A group of divers may make a surf-entry in buddy teams and meet beyond the surf zone at the diver's flag. Once safely through the surf, all equipment should be checked. Even a moderate surf can knock equipment out of adjustment or tear it away.

Sand may have entered the mask, regulator, or fins after the diver has passed through the surf. Divers should take time to remove the sand before continuing the dive. Sand in the exhaust valve of a regulator can cause it to seal improperly, permitting water, as well as air, to enter the mouthpiece when inhaling. Sand in the fins, though only mildly irritating at first, may cause a painful abrasion by the end of a dive.

Exiting the water through the surf involves performing the same procedures used to enter, except in reverse order. The diver should wait just seaward of the surf for a small set of waves. When a set has been selected, the diver should begin swimming shoreward (while keeping an eye on the incoming waves) immediately after the passage of the last of the larger waves. The smaller waves breaking behind will assist the diver's progress toward the beach. Using this assisting wave action, the diver should swim toward the beach until reaching waist-deep water. At this point, while there is still enough water for support and balance, divers should pivot around, face the waves, and plant their feet firmly. The diver should then stand up, and, bending at the knees and hips enough to maintain balance, back out of the water. When exiting with a float, divers should position it down current or push it ahead of them to avoid becoming entangled in the towline. As soon as the divers are out of the water, they should turn; only then should they remove their fins.

If knocked over by surf action after standing up, divers should not try to stand again but should let the waves carry them onto the beach. Hands and fins should be dug into the bottom to prevent being swept seaward by the backwash. On reaching shore, the divers should crawl out of the surf on their hands and knees.

10.2.2 Through Surf on a Rocky Shore

Before entering surf from a rocky shore, divers should evaluate wave conditions and should not attempt to stand or walk on rocks located in the surf zone. Instead, divers should select the deepest backwash of the last large wave of a series and enter the water; the backwash should carry the diver between the larger rocks. Every effort should be made to swim around the rocks rather than over them. Divers should stay in the small deeper channels between rocks and maintain a prone swimming position facing the next oncoming wave. They should kick or grasp a rock to keep from being carried back toward the shore and then kick seaward after the wave passes.

When exiting on a rocky shore, divers should stop outside the surf zone to evaluate the wave conditions and should then exit toward the beach on the backside of the last large wave of a series. As momentum from the wave is lost, divers should kick or grasp a rock to avoid being carried seaward by the backwash. Divers should maintain their position, catch the next wave, and thus move shoreward, exercising caution over slippery rocks.

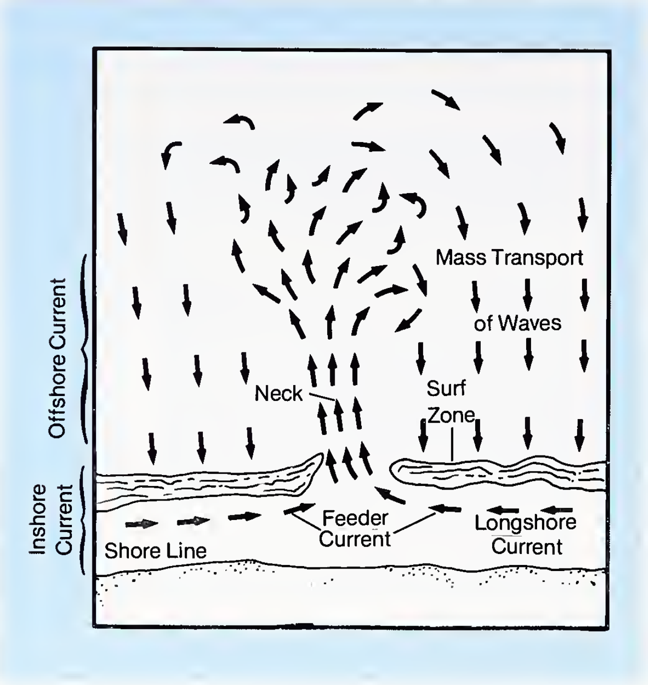
10.2.3 Through Shore Currents

In and adjacent to the surf zone, currents are generated by 1) approaching waves (and surf); 2) bottom contours and irregularities; 3) shoreline geography; and 4) tides. When waves approach the shore at an angle, a longshore current is generated that flows parallel to the beach within the surf zone. Longshore currents are most common along straight beaches. The current velocity increases with 1) breaker height; 2) increasing angle of the breaker to the shore; 3) increasing beach slope; and 4) decreasing wave period. The velocity of longshore currents seldom exceeds 1 knot (0.5 m/s). Wave fronts advancing over non-parallel bottom contours are refracted to cause convergence or divergence of the energy of the waves. In areas of convergence, energy concentrations form barriers to the returning backwash, which is deflected along the beach to areas of less resistance. These currents turn seaward in concentrations at locations where there are 'weak points,' extremely large water accumulations, gaps in the bar or reef, or submarine depressions perpendicular to shore, and form a rip current through the surf (Figure 10-2).

The large volume of returning water has a retarding effect on the incoming waves. Waves adjacent to the rip current, having greater energy and nothing to retard them, advance faster and farther up the beach. Rip currents may transport large amounts of suspended material. A knowledgeable and experienced diver can use rip currents as an aid to swimming offshore. A swimmer caught unsuspectingly in a rip should ride the current and swim to the side, rather than swimming against the current. Outside the surf zone the current widens and slackens, which permits the diver to enter the beach at another location. Rip currents usually dissipate a short distance seaward of the surf zone.

Most shorelines are not straight. Irregularities in the form of coves, bays, and points affect the incoming waves, tidal movements, and current patterns. When preparing for beach entries and exits, a diver should

Figure 10-2
Near-shore Current System



Source: Baker et al. (1966)

take wave approach, shoreline configuration, and currents into account. Entries and exits should be planned to avoid high waves and to take advantage of current movements. Divers should avoid dives that require swimming against the current and should never undertake a dive from an ocean beach without considering these factors. Hypothetical beach configurations, wave approaches, and current diagrams are shown in Figure 10-3 to aid divers in planning beach-entry dives.

10.2.4 From a Coral Reef

Diving operations from a reef should be planned, if possible, to take place at high tide when water covers the reef. For a diver wearing equipment, walking on a reef is hazardous. Footing is uncertain, reefs are generally pocked with holes, and areas that look solid may break under a diver's weight.

NOTE

Coral shoes or hard-sole neoprene boots should be worn around coral.

In some instances, there may be an area on the shore side of the reef where the water is deep enough for swimming. In this case, the outer side of the reef will break up the wave action sufficiently to allow passage over the inside calm area without difficulty. If a channel can be located that will allow passage through the reef, the diver should follow it, submerged if possible, into deep water. If a satisfactory passage cannot be located, the diver should approach the edge of the reef, wait for a wave to pass, and slip over.

10.3 DIVING FROM A STATIONARY PLATFORM

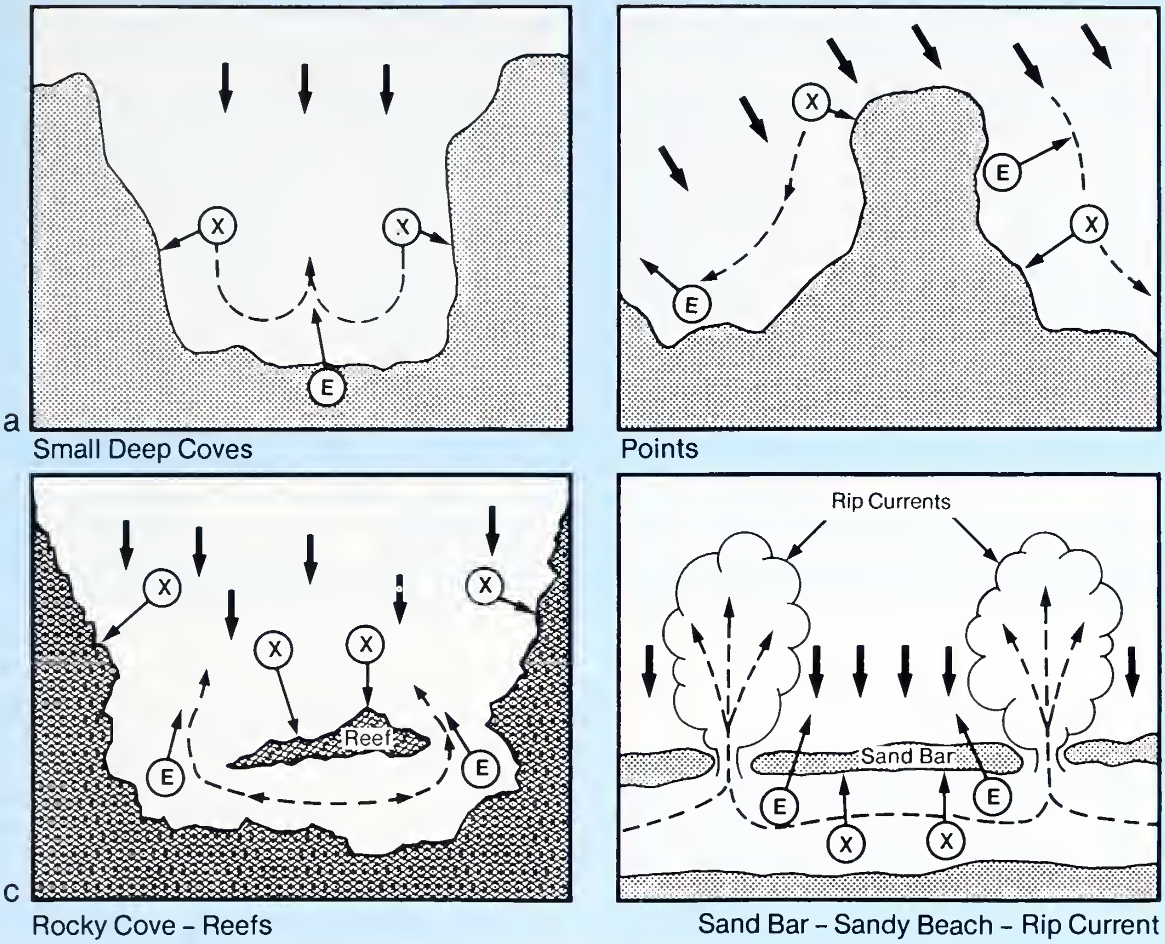
Diving from a pier or platform rather than directly from the shore offers many advantages. Deep water can be entered without having to traverse a surf line, rocks, or other obstacles. Also, if the dive site is under or close to a pier, surface-supplied diving equipment can be used. In addition, all required equipment can be transported by vehicle directly to the dive site.

Ladders should be used to get as close to the water as possible before entry. Any approved entry technique, such as stepping, can be used safely for heights up to 10 feet (3.0 m). The roll-in method shown in Figure 10-4 is not recommended for heights greater than 3 or 4 feet (0.9 to 1.2 m) above the water. Immediately prior to entering, the diver should carefully check for floating debris or submerged obstructions. Floating debris is common around a pier, and pilings often rot or break off just below the waterline. Divers should not jump into an area that has not been examined beforehand or where the water is not clear enough to see to the depth of the intended dive.

If the dive is to be conducted from an ocean pier or other high platform and no ladder is available, heavy gear can be lowered into the water and divers can make a shore entry with a snorkel, equipping themselves with scuba at pierside. If conditions make a shore entry impossible, using a small boat is advisable. When swimming under a pier or platform, divers should be submerged whenever possible to avoid contact with pilings, cross-supports, and other potentially hazardous objects.

When exiting the water onto a pier or platform, the diver should stop at the ladder to remove his or her fins. (The ladder should extend 3 to 4 feet (0.9 to 1.2 m) into the water.) Climbing a ladder with fins is awkward and dangerous and should be avoided unless the ladder is designed specifically for use with fins (see Figure 10-5). Tanks and other cumbersome equipment should also be removed and tied securely to a line and be hauled up after the diver reaches the top of the pier. Piers and docks often contain fishing lines, and care must be taken to avoid being hooked or becoming entangled in these lines.

Figure 10-3
Shore Types and Currents



E = entry; X = exit.

Heavy arrows indicate direction of wave approach; dashed lines represent path of currents, while direction is shown by light arrows.

Source: NOAA (1979)

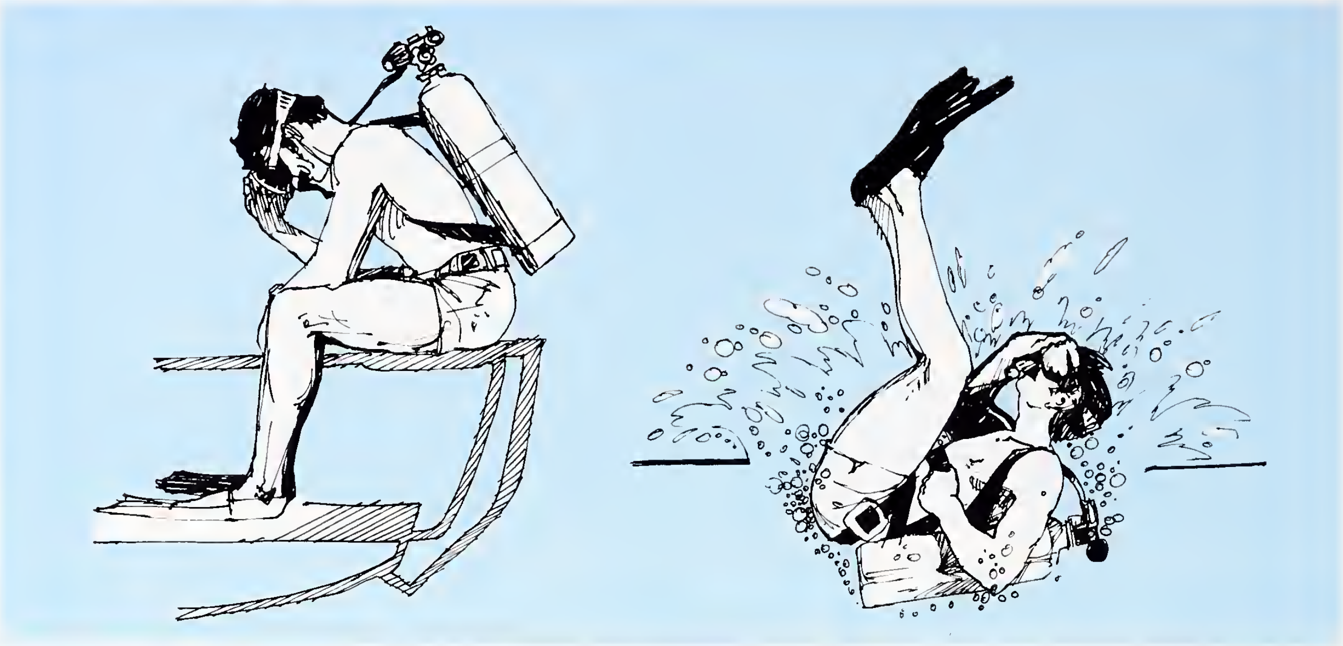
10.4 DIVING FROM A SMALL BOAT

A small boat is probably the most common surface-support platform used by divers with self-contained equipment. Configurations and types of small boats vary greatly and range from small inflatable boats to larger solid-hulled vessels. A boat used as a platform should:

- Be equipped with a means for divers to enter and leave the water easily and safely
- Be seaworthy and loaded within the capacity recommended by the manufacturer for the expected water conditions
- Be large enough to accommodate all members of the dive party, the diver's life-support equipment, and any special equipment being used in support of the dive
- Provide some shelter in cold or inclement weather for the dive party en route to the dive site and, after the dive, back to shore
- Be maintained properly and in good repair
- Carry a diver's flag (see Table 14-2).

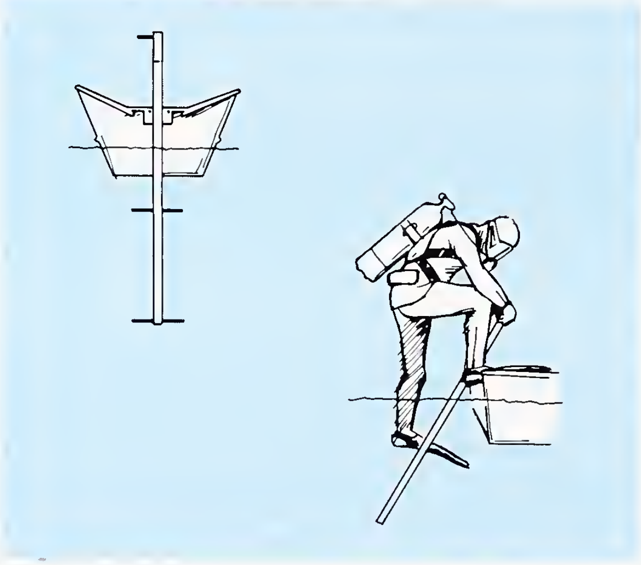
Small boats used to tend divers can be either anchored or unanchored. When anchored, the boat should be positioned downstream of the site for easy access when divers surface, and a surface float should be streamed off the stern. Even anchored boats need to be able to move immediately in case an incapacitated diver must be recovered; a buoyed anchor line facilitates a quick getaway. The operator in the boat should keep a constant watch on the diver's bubbles, and great care should be taken to stay clear of divers if an engine is in gear. When tending without an anchor, the operator

Figure 10-4
Entering the Water Using the Roll-In Method



Source: NOAA (1979)

Figure 10-5
Transom-Mounted Diver Platform



Source: NOAA (1979)

should drop the divers off upstream of the site. The boat should then remain downstream of the site during operations. Drift-diving with a surface float provides an effective method for keeping the boat in position for pickup.

10.4.1 Entering the Water

Entering the water from a small boat can be accomplished safely by several methods. Sitting on the gunwale and rolling into the water is considered best if the distance is not greater than 3 to 4 feet (0.9 to 1.2 m) (Figure 10-4). The diver should examine the area to be entered to ensure that it is clear, sit on the gunwale facing the center of the boat with both feet inside, and lean forward to counterbalance the weight of the equipment. When ready to enter, the diver should simply sit up, lean backward, and let the weight of the diving equipment carry him or her over the side. A second method of entry is the 'step-in' method, which is generally used when entering the water from a larger boat. The diver should step onto the gunwale, bend slightly forward at the waist, and step off into the water.

When entering the water using these methods, the diver should always hold the face mask firmly in place. Also, any required equipment that cannot be carried conveniently and safely should be secured to a piece of line, hung over the side, and retrieved after entry.

As a general rule, the diver should always enter the water slowly, using the method that will result in the least physical discomfort and disturbance to equipment. Each diver should determine the method best suited to various water conditions.

10.4.2 Exiting the Water

When exiting the water into a boat, there are two general rules to remember and follow. First, exiting actually begins while the divers are still submerged. While ascending, divers should look upward continuously to ensure that the boat is not directly overhead and that they will not strike it when surfacing. Holding an arm over the head during ascent is also a good practice. Exhaling during the ascent will produce bubbles, which will alert surface personnel that the diver is ascending. Second, after surfacing, the diver should not attempt to enter the boat wearing tanks or other heavy equipment unless the ladder is strong enough to handle the combined weight of diver and equipment. The diver should remove the tanks and obtain assistance from someone in the boat or from another diver in the water before climbing aboard. Rails extending above the sides of the boat are useful as handrails to support the diver as he or she climbs into the boat.

Probably the most widely used method of returning to a small boat is via a diver's ladder. Ladders also provide a secure point for divers to grasp while they are still in the water. A ladder may be built in many configurations but should have these general characteristics:

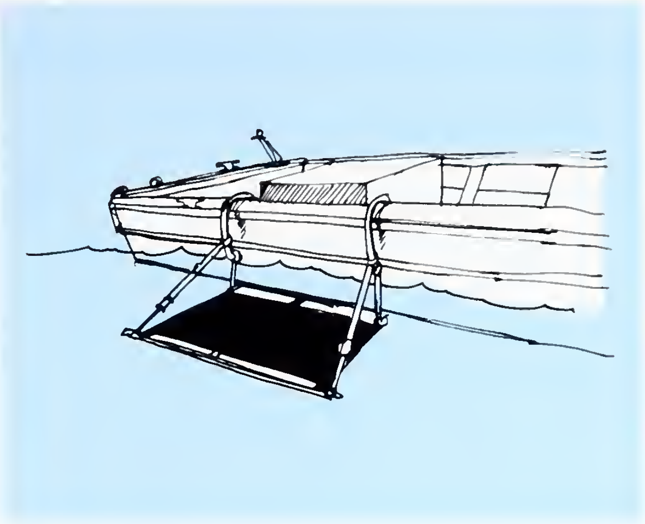
- It should extend below the surface of the water 3 to 4 feet (0.9 to 1.2 m), providing a place for the diver to stand and hold on while removing equipment.
- It should be strong, well built, and capable of being securely fastened to the side so it will not shift when subjected to the action of the seas and the diver's weight.
- It should be wide enough to accommodate the diver comfortably.
- It should be angled away from the boat to permit easier ascent.
- It should have rungs that are flat and wide.

Modifying conventional ladders to fit small boats is unsatisfactory because these ladders are closed on both sides by rung support shafts, are difficult to climb with equipment, and hang too close to the boat to provide sufficient toe space.

Figure 10-5 shows a ladder that is designed to allow a fully equipped diver to re-enter a small boat with safety and ease even in strong currents. The most important features of the ladder are lack of side supports ('open step' design), its slope, and its ability to be positioned on the transom of the boat. With a ladder of the open step type, divers can use the inner sides of their feet to locate the ladder rungs and can then step onto the rung from the side. The angle between the shaft and the transom should be 35 to 40 degrees.

Positioning the ladder on the transom (the strongest part of the boat) is particularly important in rivers because the boat partially protects the diver from the force of the current and because the diver can climb out of the water parallel to the current. If conventional ladders positioned on the side of the boat are used, the current may push the diver sideways.

Figure 10-6
Side-Mounted Diver Platform



Source: NOAA (1979)

The ladder should extend about 30 inches (77 cm) below the water's surface to allow diver access. The ladder should have a handle only on the side next to the motor, so the diver can pass unhampered on the other side.

Another method of assisting a diver into a small boat is the use of a platform rigged to the stern or the side of the boat and suspended just below the surface of the water. A diver can swim onto the platform, sit securely while removing equipment, and then stand up and step safely into the boat. A hand- or arm-hold should be provided. A portable, easily stored platform (Figure 10-6) can be constructed from either wood or metal.

10.5 FRESH WATER DIVING

There are thousands of square miles of fresh water in the United States. The five Great Lakes alone have a total area of 95,000 square miles (2,460,500 sq km), and the two-thirds of these lakes that lie within U.S. boundaries represent almost half of the fresh water acreage in the country.

Basic techniques for diving in lakes, rivers, and quarries are much like those used in ocean waters. However, some differences should be noted. For example, depth gauges are calibrated for seawater density, and adjustments must be made to achieve accuracy in fresh water (see Section 10.12.5). Buoyancy requirements also are somewhat different for fresh and salt water.

10.5.1 Great Lakes

Great Lakes divers need to be aware of the temperature changes that occur with changes in depth and season. In a typical fresh water lake, the upper layer (epilimnion) temperature generally ranges between 55 and 75°F (13 and 24°C) in late summer. However, the waters below the thermocline (hypolimnion) approach the temperature of maximum density for fresh water, 39.2°F (4°C). Consequently, divers working below the thermocline, which averages 60 feet (18.3 m) in these lakes in late summer, must plan to use buoyancy control and thermal protection.

During the winter months, the water temperature in the Great Lakes ranges between 32°F (0°C) near the surface and 39.2°F (4°C) on the bottom; during this period, a significant portion of the Great Lakes is ice covered. Occasionally, divers are required to work under 2 to 16 inches (5.1 to 40.6 cm) of ice to make observations, collect samples, or maintain scientific equipment. Diving under ice is particularly hazardous, requires special techniques and equipment, and should be undertaken only when absolutely necessary (see Section 10.9). Divers and surface support personnel operating in the lakes may be subjected to atmospheric temperatures of -30°F (-34°C), with wind chill factors approaching -100°F (-73°C).

Underwater visibility in the Great Lakes ranges from about 100 feet (30.5 m) in Lake Superior to less than 1 foot (0.3 m) in Lake Erie. Visibility is influenced by local precipitation and runoff, nutrient enrichment, biological activity, local bottom conditions, and diver activity. Significant seasonal variations also occur in these waters.

From September to December, storms and severe wave conditions can be expected in the Great Lakes. Divers working offshore at these times must use sturdy vessels and monitor weather forecasts. Because swift currents may be encountered in rivers and straits connecting with the lakes, Great Lakes divers must use considerable caution and be properly trained in the techniques of diving in currents (see Section 10.15).

10.5.2 Inland Lakes

Other lakes in the United States vary from clear mountain lakes with low sediment input to reservoirs, sediment-laden rivers, and glacial lakes, which usually have a milky appearance. When planning a lake dive, bottom terrain is as important a consideration as underwater visibility. Lakes may have vertical rocky sides, rocky outcrops, ledges, and talus slopes, or they may be sedimentary and composed primarily of old farm land. Algal blooms often occur in lakes during the warmer months and may completely block the light, even at shallow depths. Thermoclines also occur, and temperature and underwater visibility may vary greatly.

Old cables, heavy equipment, electric cables, rope, fishline, fishing lures, and even old cars are often found on lake bottoms. Many lakes have never been cleared of trees, barns, houses, water towers, and other objects. The bottom sediment of lakes is easily stirred up, as is sediment that has settled on lake-bottom trees or brush. Divers should stay off the bottom as much as possible and move slowly when forced to work on the bottom.

10.5.3 Quarries

Artificial water systems such as reservoirs and flooded strip mines, gravel pits, or stone quarries are popular spots for diving. In some areas, they represent the only place for diving, and in other regions they are used primarily for diver training. Quarries usually are deep; their water originates from seepage in the surrounding water table. For this reason, the water usually is low in nutrients and significantly colder than water in areas primarily fed by runoff. As the water near the surface warms up during the summer months, a sharp thermocline is created that must be taken into account when dressing for a quarry dive. Quarries are used frequently as dump sites for old cars and a variety of junk, and quarry divers must beware of becoming snagged on sharp metal or monofilament line, especially when the sediment is stirred up and visibility is reduced.

10.6 OPEN-OCEAN DIVING

Researchers have recently become interested in observing and sampling pelagic organisms directly in the open ocean instead of collecting specimens using such conventional techniques as Niskin® bottles, grabs, or nets. However, because open-ocean (also termed blue-water) diving does not provide a fixed frame of reference, divers performing open-ocean dives may become disoriented because they have a reduced awareness of depth, buoyancy, current, surge, other divers, marine organisms, or, occasionally, even of the direction of the surface (Heine 1985). Special techniques have therefore been developed to aid the diver operating in the open ocean to carry out scientific tasks safely.

Blue-water diving is usually done from a small boat to facilitate diver entry, exit, and maneuverability and to minimize the 'sail' area, which reduces drift and the consequent dragging of divers through the water. Even when operations are being conducted from a large vessel, a small boat should be used to tend the divers because wind and surface currents often carry a larger boat away from the actual dive site.

Open-ocean dive teams generally consist of a boat operator (who remains in the boat), a safety diver, and as many as four or five working divers. After reaching the dive site, a downline about 100 feet (30 m) long, loaded with 5 to 10 pounds (2.3 to 4.5 kg) of weight and knotted at specific depths, is passed from the boat through a surface float and lowered to serve as a safety line for the divers (Figure 10-7). This line is then secured to the surface float and to the small boat. A 4-foot (1.2 m) sea anchor is frequently used to reduce drift caused by wind; the anchor can be attached to a loop in the downline at the surface float or to a separate float to keep it from collapsing and sinking if the wind dies. To mark the dive site, it is useful to drop a small open jar of fluorescein dye into the water. The vertical column of dye emitted as the jar descends will be distorted by currents, giving a visual display of the current pattern in the water column (see Section 9.8.2).

Because of the absence of any visible reference and the inherent danger of drifting away or down, all open-ocean divers are tethered at all times to the safety line via an underwater trapeze. The trapeze can be configured from any bar or ring that accepts clips and shackles easily. Figure 10-8 shows examples of three types of trapezes that have been used for this type of diving.

In conventional diving, buddy divers swim together; in open-ocean diving, however, the safety diver serves as the buddy diver for all of the divers on the team. As shown in Figure 10-7, all divers are tethered to the trapeze by means of lines approximately 30 to 50 feet (9.1 to 15.2 m) long; the length of the line depends on underwater visibility and the task being undertaken. To avoid kinking, tethers should be braided lines. A good rule of thumb is to restrict the length of the tether to about 50 to 75 percent of the nominal underwater visibility distance (Heine 1985). The exception to this rule is the safety diver's tether, which should only be about 3 feet (0.9 m) long.

Because tethers of a fixed length tend to droop and become tangled, they should be designed to remain taut at all times, which also facilitates line-pull signalling. This can be achieved by weighting the end nearest the safety diver with a 4 to 8 ounce (113 to 227 gm) fishing weight. The tether then passes freely through the metal loop on the end of a swivel clip (Figure 10-8); these clips are attached to the trapeze, which is located near the safety diver. Thus, as the working diver swims away from the safety diver, the tether pays out smoothly, and, when the diver returns, the tether retracts as the weight sinks. In conditions of low visibility, tether lines can be shortened by tying a knot on the weight side of the tether, thus shortening the length available to pay out. The other end of the tether should be connected to the diver's buoyancy compensator or to a separate harness. If the quick-release shackle is attached to the diver's buoyancy compensator or harness (rather than to the tether), it can be released by pulling it away from the diver's body, which ensures that it will release.

Figure 10-7
Down-line Array for Open-Ocean Diving

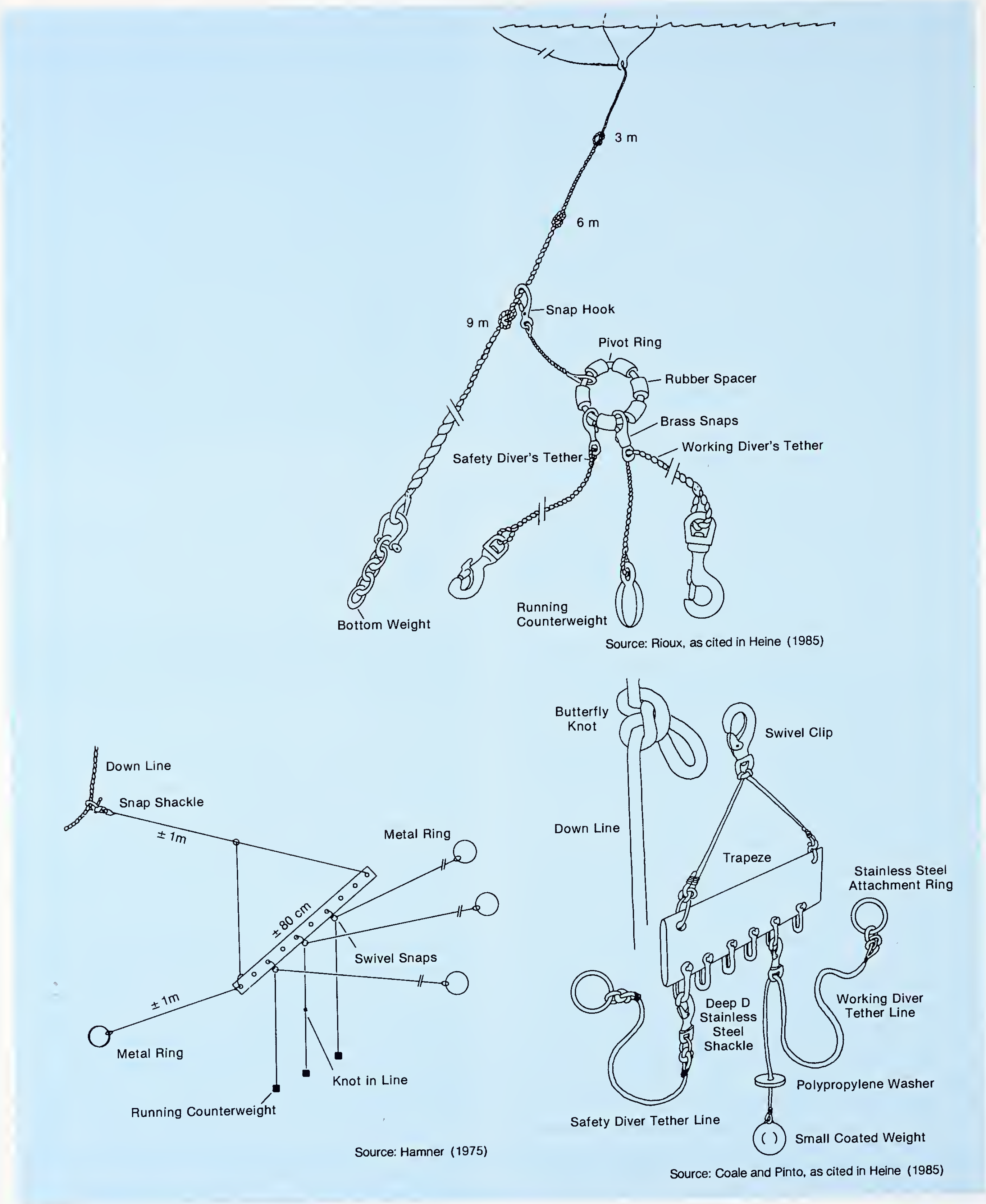
Adapted from Hamner (1975)

WARNING

Tethers Should Not Be Attached to a Diver's Weight Belt, Because Ditching or Losing the Belt Would Add Excessive Weight to the Trapeze Array

Before starting a blue-water dive, all equipment must be checked and the divers must all be sure that they understand the diving signals, especially the line-tug signals, that will be used. The safety diver enters the water first, but all of the divers usually descend down the line together to connect the pivot ring to the vertical line and to prepare the tethers. During the dive, the safety diver monitors the tethers, keeps a lookout for hazards, and supervises the dive. The safety diver maintains visual contact with the other divers and can attract their attention by tugging at their tethers. The boat operator can signal the safety diver by pulling on the vertical line. In this way, the entire team can communicate and be alerted to ascend at any time during the dive. A good practice is to have each diver run the tether through the palm of one hand so that the line-tugs can be detected easily. The safety diver can move the pivot ring up and down the vertical line to any of the knotted stops, as required, and can thus control the maximum depth of all of the divers. The safety diver can also terminate the dive or send

Figure 10-8
Three Multiple Tether Systems (Trapezes) Used for Open-Ocean Diving



Source: Rioux, as cited in Heine (1985)

Source: Hamner (1975)

Source: Coale and Pinto, as cited in Heine (1985) any diver up if the situation warrants such action. Divers can ascend at will by signalling their intent to the safety diver, unclipping their tethers at the pivot ring, and ascending the vertical line to the boat. It is important that the divers hold the downline when ascending so that they do not drift away from the boat.

If scientific or diving equipment is hung on the downline, it can be attached to the line at the appropriate depth as the line is deployed, which makes it unnecessary for the divers to carry the equipment. Any equipment hung on the downline should be positioned above the trapeze and safety diver, and the weight of the equipment must not be so great that it overweights the downline. Divers working below the trapeze must be careful to avoid entanglement in the weighted tethers, which would envelop the safety diver in a cloud of bubbles and reduce his or her ability to see. If a second line is deployed for equipment, it must be separated clearly from the safety line and should not be used as an attachment for tethers.

In addition to diving, safety, and scientific equipment, most open-ocean divers carry a shark billy (see Section 5.7). According to experienced blue-water divers at the University of California at Santa Cruz:

> Twenty percent of all the blue water dives performed by our group in the central north and south Pacific gyre systems and the eastern tropical Pacific were aborted due to the persistent presence of sharks, specifically oceanic white tip sharks. In all cases they were spotted first by the safety diver. This underscores the value of the safety diver and a routine abort plan and the utility of the shark billy (Heine 1985).

Divers generally work in an area upstream of the trapeze, which allows them to collect fresh, undisturbed samples and to stay in a single area in sight of the safety diver. As they perform their tasks, the divers scan their surroundings and make visual contact with the safety diver. The safety diver constantly monitors the surroundings, checks for sharks, keeps an eye on the divers and the downline, and generally monitors the progress of the dive. During the course of the dive, the safety diver maintains contact with the divers by periodically tugging on the divers' tethers to ensure that they are comfortable, their air supply is adequate, and they are responding to pull signals appropriately. If a diver requires minor assistance, the safety diver signals another diver to go to his or her aid. Before the safety diver becomes involved in helping another diver, he or she must first signal another diver to act as the temporary safety diver. There must always be someone acting as safety diver (Heine 1985).

As with any specialized diving, open-ocean diving requires individualized training and practice. Readers should consult a specialized open-ocean diving manual for further details about this type of diving.

10.7 CAVE DIVING

Cave diving is a specialized form of diving that can be performed in both inland fresh waters and ocean 'blue holes.' To scientists, caves offer new laboratories for research. In cave diving, the emphasis should be placed on developing the proper psychological attitude, training in specialized techniques and life support systems, dive planning, and the selection of an appropriately trained buddy diver.

WARNING

Only Experienced and Specially Trained Divers Should Undertake Cave Diving. Open-water Experience Is No Substitute for Cave Diving Training

The cave diving environment is alien to humans, because it involves both the underwater environment and the limited-access, limited visibility, confined space environment typical of caves. Examples of the special hazards that may be encountered in cave diving are: the absence of a direct and immediate ascent route to the surface, the sometimes instantaneous loss of visibility because of silting or failure of the diver's light, and the entanglement and impact hazards associated with being in a confined, enclosed area. These and other factors all have an effect on the psychological composure of divers and their ability to cope with stressful situations. Improperly trained divers, unaware of the hazards unique to cave diving, often panic and drown when they encounter situations that are in fact normal for the cave diving environment. It is imperative that divers develop the proper psychological attitude before they consider conducting a cave dive. Completion of a standard scuba diving course does not prepare a diver for the special perils faced in cave diving.

Before taking a course in cave diving, the diver-student must have enough open-water experience to feel psychologically and physically comfortable under water. Because their lives may one day depend on the quality of instruction received, persons contemplating taking a course should select one taught by a mature and nationally certified cave diving instructor. A good cave diving course should include prescreening of potential divers, at least 100 hours of training in underwater work, and instruction in line safety, the elements of buoyancy control, buddymanship, dive planning, equipment handling, and dive theory. Three basic rules of safe cave diving that must be adhered to by every diver are:

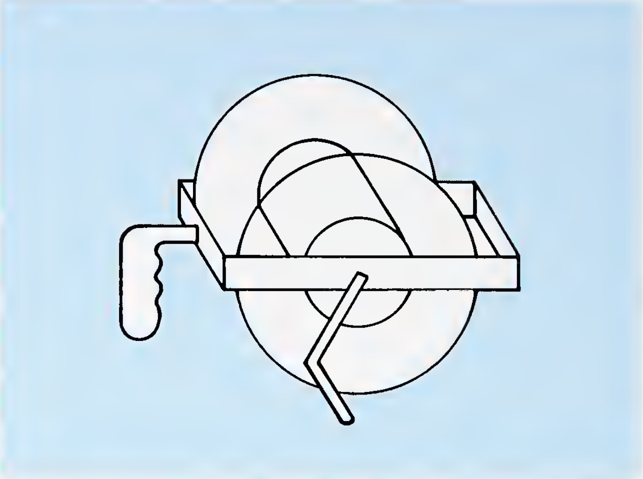
(1) Always use a continuous guideline to the surface.
(2) Save two-thirds of the total air supply for returning to the surface.
(3) Carry at least three lights during the dive.

A common hazard in cave diving is the presence of silt. To minimize silting, cave divers must be specially trained to swim horizontally and to maintain proper buoyancy at all times.

A safety reel and line are the cave diver's link to the surface and survival. Several kinds of lines are used for safety and navigation. Temporary lines are the most commonly used and consist of a safety reel and line. A suitable safety reel should feature a line guide, drum, buoyancy chamber, a good turns ratio, and be capable of carrying approximately 400 feet (122 m) of 1/16 inch (1.6 mm), 160-pound (72.6 kg) test to 1/8 inch (3.2 mm), 440-pound (199.6 kg) test braided nylon line. The reel should be neutrally buoyant, compact, and rugged (Figure 10-9). Large reels and lines create extra drag for the diver and require extra exertion.

When running a safety line, the diver with the reel should maintain tension. The line should be tied within surface light, and safety wraps should be made approximately every 25 feet (8.3 m). The line should be centered in the cave as much as possible. The reel-diver is first in and last out. The buddy is responsible for unwrapping the safety wraps on leaving the cave and for providing light for the diver tying or untying the line. Physical contact with the line should be avoided except when visibility decreases. In some cases, cave divers will use permanent lines for mapping or to permit a more complete exploration of a cave. Novices should use temporary lines and should not attempt to follow permanent lines unless they have a thorough knowledge of the cave. The technique for laying and retrieving a safety line is unique to cave diving and should be practiced until it becomes second nature, because it could save one's life in a total silt-out, where there is a complete loss of visibility. It is important to remember that in cave diving the safety line is not a tow line and should not be used for support.

Figure 10-9
Safety Reel Used in Cave Diving



Source: NOAA (1979)

Standard cave diving life-support systems should include:

- double tanks
- double manifolds
- two regulators
- submersible pressure gauge
- buoyancy compensator with automatic inflator hose
- depth gauge
- watch
- decompression tables
- wet or dry suit
- safety reel with line
- lights
- compass
- slate
- pencil.

The larger capacity double-tank arrangement recommended for cave diving has an 'ideal' or double-orifice manifold. This system manifolds two tanks together with a common gas supply and uses two regulator adaptors. If one regulator fails, that regulator may be shut off while the second regulator continues to function without interruption and with access to both gas cylinders. One of the regulators also should have a 5-foot (1.5 m) hose so that divers may share their gas supply when maneuvering out of tight situations.

Although the need for lighting in cave diving is obvious, the lighting taken on cave dives is often not adequate for safety. Each diver must carry at least 3 lights, with the brightest being at least 30 watts. Backup lights can be of lower wattage, but they must also be dependable and of high quality.

All cave diving equipment must be checked and rechecked by each member of the dive team before submersion to ensure proper functioning, ease of operation, and diver familiarity. During this time, the smooth operation of backup equipment should also be verified and the dive plan should be reviewed for the last time.

The maximum recommended number of cave divers per team is three. Larger groups cannot handle the integrated 'buddymanship' necessary to maintain the constant contact so essential in cave diving. For further information about cave diving, readers should write to the National Association for Cave Diving, Box 14492, Gainesville, Florida 32604, or the National Speleological Society's Cave Diving Section, 3508 Hollow Oak Place, Brandon, Florida 33511.

10.8 COLD-WATER DIVING

Diving in cold water is associated with several equipment problems not found in warmer waters; the major difficulty involves the regulator. Most single-hose regulators have a tendency to freeze in the free-flow position after approximately 20-30 minutes of extreme cold-water exposure. However, several models are available that are designed to resist freezing and that use a special antifreeze-filled housing system. The standard double-hose regulator rarely develops this freezing problem. If a regulator begins to freeze up, the dive should be aborted immediately. An early sign that freeze-up is about to occur is the presence of ice crystals on the tongue. Second-stage freeze-up is generally caused by moisture in the exhaled breath, which then condenses and freezes on the metal parts.

Another cold-water diving problem is that the diver's mask is more likely to fog or freeze in cold water, which means that a non-irritating defogging agent should be applied to the mask before diving. Partially flooding the mask and flushing seawater over the faceplate will relieve this condition temporarily. Divers must be careful to avoid inhaling cold seawater through their noses, because introducing very cold water into the mask often causes divers to inhale involuntarily.

Keeping the diver's body warm is the most important requirement in cold-water diving (Figure 10-10). The standard foamed-neoprene wet suit has been used in 29°F (2°C) water for dives lasting longer than an hour, but it is doubtful whether the divers on these dives were comfortable or thermally safe. A major drawback of wet suits is that, by the time the dive is over, the diver is wet and will therefore probably continue to lose body heat even after leaving the water. Further, the loss of foam thickness with depth drastically reduces the efficiency of any wet suit for cold water diving much below 60 feet (18.3 m).

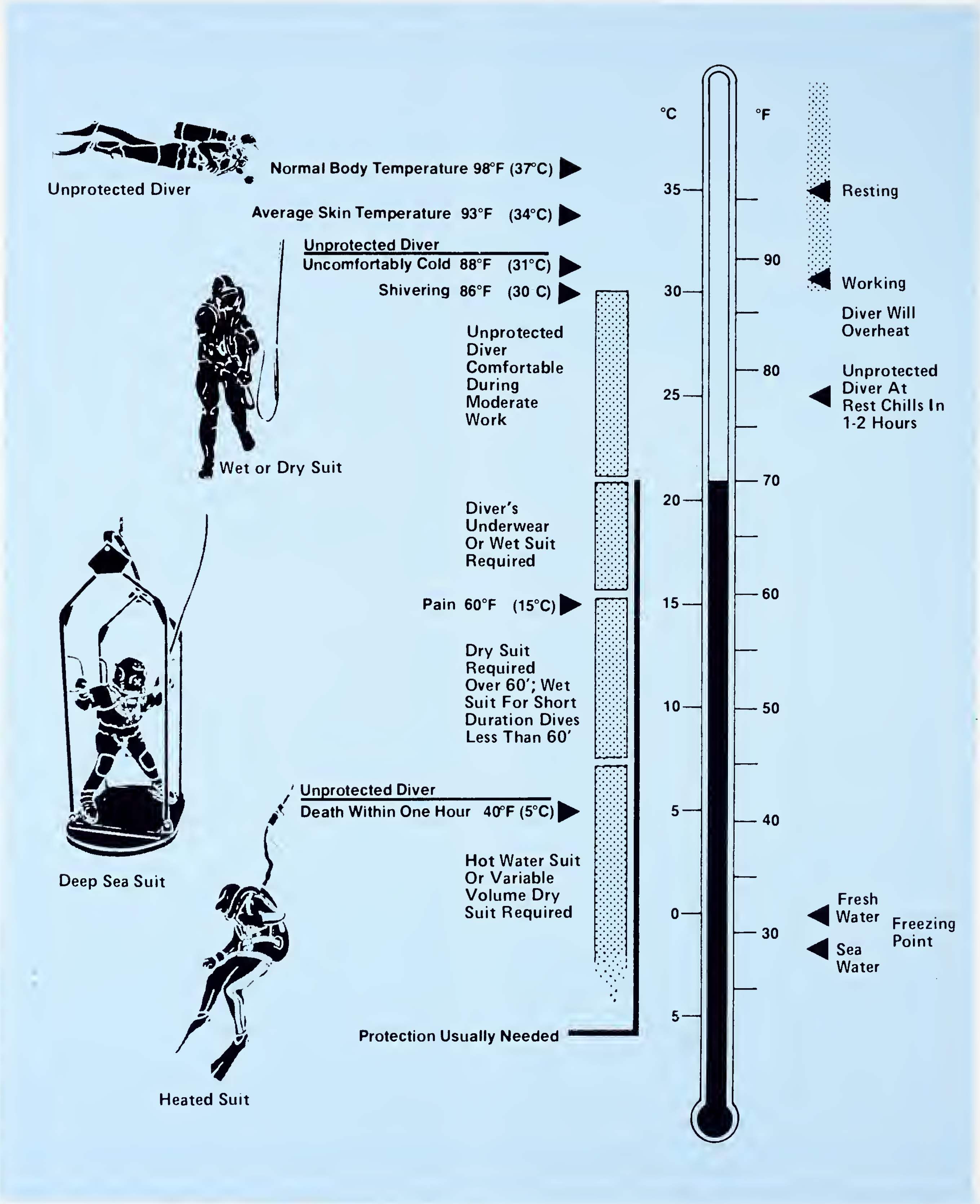
Two types of diving dress have been used with success under severe thermal conditions: the hot-water wet suit, which provides a continuous flow of preheated water to the diver, and the variable-volume dry suit, which allows the diver to control the amount of air in the suit and thus its insulating capability. (A more detailed description of these suits is presented in Section 5.4.) Except for the hot-water wet suit, no dry or wet suit provides complete protection of the diver's hands for long periods. As the extremities become cold and dexterity is lost, the diver becomes less efficient and should terminate the dive. The use of heavy insulating socks under the boots of a wet or dry suit will help to keep the feet warm. Hands should be protected with gloves or mittens having the fewest possible digits; the loss of manual dexterity associated with the use of gloves or mittens is overridden by the added warmth they provide. Filling the gloves or mittens with warm water just before the dive begins is also recommended.

Heat loss from the head can be reduced by wearing a second well-fitted neoprene hood over the regular suit hood. Wearing a knitted watchcap under the hood of a dry suit is especially effective in conserving body heat. If the cap is pushed back far enough to permit the suit's face seal to seat properly, the diver's head will be kept relatively dry and comfortable. With a properly fitting suit and all seals in place, a diver can usually be kept warm and dry, even in cold water, for short periods.

If divers and members of the surface-support crew follow certain procedures, the adverse effects of cold-water exposure can be greatly reduced. Suits should be maintained in the best possible condition, dry suit underwear should be kept clean and dry, and all seals and zippers should be inspected and repaired (if necessary) before the dive. During the dive, divers should exercise as much as possible to generate body heat.

Dives should be terminated immediately if the diver begins to shiver involuntarily or experiences a serious loss of manual dexterity. Once involuntary shivering begins, the loss of dexterity, strength, and ability to function decreases rapidly (see Section 3.4). After leaving the water, cold-water divers are often fatigued, and, because heat loss from the body continues even after removal from cold water, such divers are susceptible to hypothermia. Flushing the wet suit with warm water as soon as the diver surfaces has a comforting, heat-replacing effect, although such flushing can cause additional body heat loss unless it is done cautiously. Facilities must be provided that allow the diver to dry off in a comfortable, dry, and relatively warm environment, so that he or she can regain lost body heat (see Section 3.4.4). Divers should remove any wet clothes or suits, dry off, and then don warm protective clothing

Figure 10-10
Water Temperature Protection Chart



Source: US Navy (1985)

as soon as possible. In cold-water diving situations that require repetitive dives, it is even more important to conserve the diver's body heat, to maintain an adequate fluid balance, and to select the diving dress carefully.

Adequate rest and nutrition are essential to providing cold-water divers with the energy necessary for this type of diving. A diver should have a minimum of 6-8 hours of sleep before the dive. Care must be taken to avoid dehydration, which can interfere with the body's thermal regulatory mechanism. Careful planning is thus of the utmost importance in all cold-water diving.

WARNING

If a Diver Is Extremely Cold, the Decompression Schedule Should Be Adjusted to the Next Longer Time

10.9 DIVING UNDER ICE

In addition to the problems and limitations of diving in cold water (see Section 10.8), there are specific precautions that must be taken when diving under ice. Diving under ice is extremely hazardous and should be done only by experienced divers who have been carefully trained.

Most ice diving is done from large and relatively flat surface ice sheets that are stationary and firmly frozen to the shore. Even at locations many miles from the nearest land, these ice caps often offer a stable working platform. However, diving from drifting or broken ice is dangerous and should only be done as a last resort. When the ice cap is solid, there is no wave action to the water; however, divers must constantly be on guard because the current beneath the entry hole can change quickly and dramatically without producing any noticeable effect on the surface. In most cases, the absence of wave action produces good underwater visibility, although under-ice diving operations conducted in areas characterized by river runoff or heavy plankton may be associated with conditions of reduced visibility.

To enter the water through ice, divers should first drill a small hole through the ice at the site to determine ice thickness and water depth. If conditions are satisfactory, the area around the site should be cleared of snow and the size of the entry determined. A hole of approximately 3 by 5 feet (0.9 by 1.5 m) allows three fully dressed divers to be accommodated at one time. If no shelter is used, a triangle-shaped entry hole works best.

Figure 10-11
Diver Tender and Standby
Diver in Surface Shelter

Photo Doug Eiser

In all diving operations under ice, there should be one surface tender for each diver and at least one standby diver (Figure 10-11). While the diver is in the water, the tender must be attentive both to the diver and surface conditions, such as deteriorating weather or moving ice. Tenders should be briefed on the diver's tasks, so that they will understand the diver's movements and be able to respond quickly in an emergency. A safety line should be tied to the diver (not to the equipment) and the other end should be tied firmly to a large fixed object on the surface. Excursions under the ice should be well planned, and the distance to be traveled under the ice away from the entry hole should be kept to a minimum; under normal circumstances, this distance should be limited to 90 feet (27.4 m) and should be extended to as much as 250 feet (45.7 m) only in unusual circumstances. Longer under-ice excursions make it difficult for the diver to get back to the entry hole in an emergency and increase the difficulty of searching for a lost diver. If divers must travel long distances under the ice, additional holes should be cut for emergency exits. Divers lost under the ice should ascend to the overhead ice cover immediately, maintain positive buoyancy, relax as much as possible to conserve air, and wait for assistance.

WARNING

Divers Lost Under the Ice Should Ascend to the Ice Cover and Wait Calmly to Conserve Air. They Should Not Search for the Entry Hole

To aid the diver to return to the entry hole, a bright light should be hung just beneath the surface. For night diving under ice, this light is a necessity; it is usually the only item required beyond those used in day-time operations. However, since cold water shortens the life of batteries, homing beacons and strobes should be checked before use. Because direct ascent to the surface is impossible when under the ice, a rapid means of determining direction often is critical. In shallow water, detours are often necessary to circumvent the 'keels' (thickened areas) built up beneath the ice. Also, because of the absence of waves, there are no ripple patterns on the bottom to aid in orientation. For these reasons, the use of a tether is absolutely essential in under-ice diving.

If there is a failure in an ice diver's primary breathing system, the diver should switch to the backup system, notify the buddy diver, and exit to the surface with the buddy diver. Because buddy breathing is difficult in cold water, all divers should practice buddy breathing before making excursions under the ice. Octopus regulators should not be used in cold water as substitutes for buddy breathing because the first stage of these regulators tends to freeze up. If a diver's exposure suit tears or floods, the diver should surface immediately, regardless of the degree of flooding, because the chilling effects of frigid water can cause thermal shock within minutes. Surface-supplied tethered diving is becoming more popular in under-ice operations because it eliminates the need for safety lines and navigation lights and provides unlimited air. The full-face masks or helmets of most surface-supplied diving systems provide additional protection for the diver's face and provide the capability for diver-to-diver and diver-to-surface communication. These added features must be weighed carefully against the burden of the added logistic support required to conduct surface-supplied diving. If the advanced dry suits now available (see Section 5.4.5) are used, the surface-supplied diver can spend long periods under the ice in relative safety and comfort.

If an under-ice dive operation is scheduled to last for more than 1 or 2 days, a tent or shed should be constructed over the entry hole (Figure 10-11). Such a shelter will protect both surface support personnel and divers from the wind and, together with a small portable heater, can provide relative comfort in these severest of diving conditions.

10.10 KELP DIVING

Kelp is found in dense beds along many of the colder and temperate coasts of the world. In the United States, these plants are found along the shore regions of the west coast. Kelp beds or forests are widely diversified both geographically and as a function of depth and temperature. Different varieties grow in different zones and support an incredible variety of sea life. Kelp will attach itself to practically any substrate (i.e., rock, concrete, steel, wreckage, etc.) and will often form a treelike structure, the base of which is a rootlike holdfast that provides a secure anchor and a home for many organisms. There is generally an area of open water between the stipes originating from one holdfast. A diver can swim between the stipe columns just as a hiker can walk between the trunks of trees in a forest on the land. Hollow floats or pneumatocysts are found at the base of the blades or fronds on many of the larger, longer kelp plants. These floats cause the fronds to float up and keep the stipes relatively upright. The floating fronds form a canopy when they have grown sufficiently to reach the surface. In many instances, this rapidly growing canopy becomes very dense and can be several feet thick on and near the surface. The canopy will usually have thin spots or openings located randomly throughout the area, and these thin spots or openings provide entry and exit points for divers. These thinner areas are easily seen from below the surface because the light penetration in these areas is much better; in addition, as a diver positioned under such a light area exhales, the rising bubbles usually float the kelp outward to form an opening that is sufficiently large to enable the diver to surface. Care should be exercised when the diver's head is out of the water, because the kelp may float back and fill in the hole and surround the diver. Although the kelp will not actually wrap itself around the diver, divers who twist around and struggle may become entangled. Training in kelp diving is necessary to master the skills to make entries and exits easily.

Equipment that is not relatively streamlined can snag and tangle in the kelp and cause problems. If the diver becomes entangled, it is important to remember that kelp is designed to withstand the pulling force of wind, waves, and currents and consequently that the tensile or stretching strength of the plant is very great. Divers wishing to break a strand of kelp should fold it to develop a sharp angle in the stipe. Pulling on the kelp will result in frustration and may cause panic. Nicking the kelp with a sharp object will separate the kelp easily, but using sharp objects such as knives needs to be done with care because of the proximity of regulator hoses and other critical paraphenalia. The easiest way to get free is to remain calm and to pull the strands away carefully with a minimum of movement.

When working from a boat, it is best to anchor in an opening so that the wind or current will drift the boat back on the anchor line to a second opening in the kelp. Divers may also anchor outside the kelp and swim in to do their work. If the boat is anchored in the kelp, the anchor will be full of kelp that must later be removed surgically.

Entry through the kelp is best accomplished by finding a thin area and making a feet-first, feet-together entry rather than a headfirst or backroll entry that could easily lead to entanglement. It is important to get through the canopy and into the open water between the stipes. Once through the surface canopy, the diver can swim with comfort in the forestlike environment. As the diver swims along, it is important to watch for the light areas that signal the thinner areas in the kelp bed. Surfacing slowly permits a diver's exhaust bubbles to assist in making an opening. When the diver approaches the surface, the arms should be raised over the head so that any kelp that may be encountered can be moved to the side easily as the diver moves upward into the hole that has been opened. Once on the surface, the diver should stay in the vertical position and should not turn around; this helps to avoid entanglement. Submerging can be accomplished easily by either exhaling and sinking or raising the arms overhead, which forces the body deeper down into the water. Smooth and slow movements make this maneuver easy and safe.

The diver who wishes to travel on the surface of a kelp bed to get back to the shore or boat has several choices. If the diver is sufficiently skilled, it is easy to use a series of breath-hold dives to move in steps to the desired location. Each step requires the diver to surface through an opening in the kelp and to take a breath or two in preparation for the next step. Another useful technique, often called the Kelp Crawl, resembles the 'dog paddle' and involves keeping the body on the surface above the kelp canopy and using the arms to pull the diver across the top of the kelp as the diver's fins make a narrow flutter kick to slide the body across the top of the floating kelp canopy. The arms should reach across the kelp in an extended position and then the hands should grasp the kelp and press down as the body is pulled over the kelp. It is important to present a streamlined surface to the kelp, since anything that extends out from the body will probably snag. Swim fins with adjustable heel straps should have the loose end of the strap on the inside rather than the outside of the buckle. Taping the loose end of a strap to the main portion of the strap is also a good solution. Wearing the diving knife on the inside of the calf rather than anywhere on the outside of the body is also a snag reducer. Kelp divers should remember that they want to move through the kelp or over the kelp in a streamlined fashion and that inflated buoyancy compensators, game bags, and tools of all kinds should be organized to present minimal problems.

Divers should also remember that kelp floats and that, in a pinch, it is possible to achieve flotation by using the kelp for support. Under windy conditions, divers should approach the stern of a small boat to avoid being pressed by the boat's movement into the kelp and becoming entangled.

The various forms of kelp may grow so that the taller kelps such as *Macrocystis* may be found growing over a forest of *Pelagophycus* (or elk kelp). This second lower canopy of kelp will further reduce the light level but will be easier to swim through than the surface canopy. All kelp beds are influenced by wind, currents, and surge, and major beds may disappear from surface view in a swift current because they are held down at a 45-degree angle. This has its advantages because the kelp will stream with the current and thus may be used as a navigational aid during the dive.

Achieving comfort and efficiency in kelp diving is the result of training and practice. Having a buddy diver along who is equally well trained is also extremely important.

10.11 WRECK DIVING

Wreck diving subjects the diver to many of the same hazards that are found in cave or ice diving. In the past 20 years, wreck diving has evolved into an activity requiring both specialized equipment and training, particularly in the case of deep wreck diving. Regardless of purpose (lobstering, artifact collecting, photography, or exploring), true wreck diving involves the diver entering the wreck. It is the act of penetrating the enclosed space of the wreck that necessitates the additional equipment and training.

Most intact wrecks are at depths in excess of 80 feet (24.4 m), because those in shallower water have been destroyed either by storms or because they were navigational hazards. After arriving on the bottom at the wreck site, the first team of divers must check the anchor of the boat for security and to ensure that the anchor line will not chafe. The path into a wreck usually has fair to good visibility. On the return trip, however, visibility may be reduced dramatically because the divers have stirred up the silt and ferrous oxide (rust) from the walls and exposed steel plates of the wreck. The reduced visibility and the confusion and anxiety caused by the many passageways, entrances, chambers, bulkheads, and tight spaces require that wreck divers use a penetration line such as a braided 1/8-inch (3.2 mm) nylon line on a reel. The line should be tied off at the wreck's entrance, payed out during entry, and reeled in during return. If the line is lost or cut, the diver should pause, allow the silt to settle, and regain his or her composure before attempting to return to the entrance. Placing the faceplate of the underwater light into the silt will reduce the ambient light level and allow the diver's eyes to adapt partially to the darkness. This will facilitate the detection of any surface light coming into the passageways and thus aid in the identification of possible exit paths.

Because of depth, the use of twin scuba cylinders, together with a pony bottle with a separate regulator, is recommended as standard wreck diving equipment. In some instances, a spare air supply and regulator should be placed outside the wreck. These precautions are necessary in case the diver becomes entangled or decompression is needed unexpectedly. During wreck diving, entanglement may be caused by objects such as monofilament fishing line, fish nets, collapsed bulkheads, or narrow spaces. A bag containing appropriate tools for artifacts, liftbags, and an upline should be carried to reduce the risk of entanglement that prevails if this equipment is carried by or attached to the diver. Most instrumentation can be strapped to the underwater light; a set of decompression tables may be attached to the light housing, reducing the amount of equipment carried by the diver but still permitting ready access to the tables if decompression is required. Although a diver inside a wreck may be tempted to breathe in the air pockets produced by previous divers, this practice should be avoided because the partial pressure of oxygen in these pockets is usually quite low and hydrogen sulfide may be present.

The water temperature around a wreck is usually low, and divers must therefore dress properly. Variable-volume dry suits or 1/4- to 3/8-inch (6.4 to 9.5 mm) wet suits should be used in water temperatures of 50°F (10°C) or less (see Section 5.4). Extreme caution must be taken not to snag the suit or equipment on the sharp objects commonly found in wrecks, such as decayed wooden decks or corroded metal bulkheads, because these hazards are frequently overgrown by algae, sea polyps, or other marine growth.

10.12 DIVING AT HIGH ELEVATIONS

The U.S. Navy Standard Decompression Tables, No-Decompression Table, and Repetitive Dive Tables were calculated and validated on the assumption that the diver started from and returned to an ambient atmospheric pressure of 1 atmosphere absolute (ATA). Consequently, these tables do not account accurately for dives conducted from ambient environments having pressures less than 1 ATA. Two sets of tables or corrections are now in use for calculating diving schedules for altitude diving: the Boni/Buehlmann tables and the Cross corrections, as modified by Bell and Borgwardt. These are described below, and representative dive profiles based on these tables are compared.

10.12.1 Altitude Diving Tables Currently in Use

The Boni/Buehlmann tables were developed by Boni and his colleagues (1976) and include no-decompression, decompression, surface interval, and residual nitrogen (called the 'repetitive timetable') tables for each 1,640 feet (500 m) of altitude up to 10,496 feet (3,200 m). The tables to 6,561 feet (2,000 m) have been tested on humans in wet dives (Boni et al. 1976). The results of 94 non-repetitive dives to depths between 52 and 98 feet (15.8 and 9.1 m) and for bottom times as long as 40 minutes were reported. The results of 184 dives under approximately the same conditions were also reported by these authors. No symptoms of decompression sickness of any kind were observed during these 278 dives. These tables require a routine decompression stop for 3 minutes at 6.6 feet (2 m) for dives within the no-decompression limits. Consequently, all dives used for testing the tables included a decompression stop for 3 minutes or longer.

The Cross corrections to the U.S. Navy tables were developed to convert the standard U.S. Navy decompression tables to tables that could be used in altitude diving. This adjustment method was first developed in 1965 by Dr. Jon Pegg but was never published. A similar set of corrections was later developed by H. J. Smith, Jr. (Cross 1967) and was subsequently published in greater detail (Cross 1970). The Cross method involves determining a theoretical ocean depth (TOD) by multiplying the dive depth by the ratio of the atmospheric pressure at sea level to that at the altitude at which the dive will be made. The TOD and the actual bottom time in the U.S. Navy tables are then used to determine the altitude diving schedule.

The theory of the Cross corrections has been examined in detail (Bell and Borgwardt 1976); the correction factors used in the Cross tables do not apply to the critical tissue pressures used in the Navy tables as safety criteria. On the other hand, in the cases studied, the Cross corrections always 'failed' on the conservative, i.e., safe, side. University of California underwater research teams have used the Cross corrections as a guide to diving in California lakes and in Lake Tahoe, Nevada (elevation 6200 feet (1890 m)). Diving schedules used have included procedures for up to three repetitive dives per day to depths of 130 feet (39.6 m). Both no-decompression and decompression dives have been conducted; no reported cases of decompression sickness have occurred in several hundred dives.

10.12.2 Comparison of Existing Tables

A comparison of the no-decompression limits given by the two altitude correction methods and the U.S. Navy tables is shown in Table 10-1. As this table shows, both the Cross corrections and the Navy tables yield no-decompression limits that are longer than those predicted by the Boni/Buehlmann tables, although in both cases the no-decompression limits are less than those that apply to sea level.

There have been no reported cases of decompression sickness in divers using the Cross corrections on dives from an altitude of 6200 feet (1890 m). The Cross corrections therefore appear to be safe. Several laboratories are continuing to study this problem, but at this time the true bends threshold for these tables has not been established. Consequently, altitude diving, and particularly decompression altitude diving, should be performed using conservative assumptions and special precautions to ensure access to emergency treatment.

10.12.3 Recommendations for Altitude Diving

The Cross corrections are recommended for general use within the no-decompression limits. Although decompression dives have been conducted using the Cross corrections, they have been relatively few and have not involved depths greater than 130 feet (39.6 m) from an elevation of 6200 feet (1890 m). In general, decompression dives at altitude should be avoided.

10.12.4 Calculations for Diving at Altitude

The Cross correction tables, as modified by Bell and Borgwardt, are shown in Table 10-2. This table is identical to that presented by Cross (1970), except that it has been modified to account for fresh water and rate of ascent. The table is used as follows:

1. The depth of the planned dive is found in the column on the left marked "Measured Depth."
2. The altitude of the dive site or the next greater altitude is found in the top row of the table.
3. The entry corresponding to the intersection point of the depth row and the altitude column marks the "theoretical ocean depth" (TOD), which, according to the assumptions of the Cross theory, yields a probability of decompression sickness equivalent to that for the altitude and measured depth of the dive.
4. The TOD and the total bottom time, including any residual nitrogen time accrued from repetitive dives, are then used with the U.S. Navy tables. The dive schedule is calculated exactly as it would be for a sea-level exposure. Each time a dive is planned, the TOD equivalent is substituted for that measured depth.
5. The ascent rate at altitude must be reduced, as shown in Table 10-2.
6. If a decompression dive is conducted (which is not recommended), the depth of the decompression stops must also be corrected, as shown in Table 10-2.

Table 10-1
Comparison of Differences in
Time Limits (in Minutes of
Bottom Time) for No-Decompression Dives

Measured Depth (ft)	USN Tables (min)	Cross Tables (min)	Boni/Buehlmann Tables (min)
60	60	40	15 (+ 3 at 2 m)
80	40	25	6 (+ 3 at 2 m)
100	25	10	4 (+ 3 at 2 m)
120	15	5	Decompression

In this example, dives are assumed to take place at an elevation of 6000 feet (1829 m).

Adapted from NOAA (1979)

Example:

Two dives are to be conducted at an altitude of 6000 feet (1829 m) on a no-decompression schedule. The first is to be to 80 feet of fresh water (ffw) (24.4 mfw) for 20 minutes; the second to 60 ffw (18.3 mfw) for 25 minutes. Find the surface interval required to complete the dive schedule in minimum time.

Solution:

From Table 10-2, the theoretical ocean depth in fsw that corresponds to a depth of 80 feet of fresh water (ffw) (24.4 mfw) in a lake whose surface altitude is 6000 feet is 97 fsw (29.6 msw) and that for a depth of 60 feet of fresh water (18.3 mfw) is 73 fsw (22.2 msw). The sea-level decompression table (Appendix B) must therefore be entered at 100 fsw (30.1 msw) and 80 fsw (24.4 msw), respectively. A 20-minute dive to a TOD

Table 10-2
Theoretical Ocean Depth (TOD)
(in fsw) at Altitude for a
Given Measured Diving Depth

	Altitude in feet										
Measured Depth*	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
		TOD in fsw at Altitude									
0	0	0	0	0	0	0	0	0	0	0	0
10	10	10	10	11	11	12	12	13	13	14	14
20	20	20	21	22	23	23	24	25	26	27	28
30	29	30	31	33	34	35	36	38	39	41	43
40	39	40	42	44	45	47	49	51	52	55	57
50	49	51	52	54	56	59	61	63	66	68	71
60	59	61	63	65	68	70	73	76	79	82	85
70	68	71	73	76	79	82	85	88	92	95	99
80	78	81	84	87	90	94	97	101	105	109	113
90	88	91	94	98	102	105	109	114	118	123	128
100	98	101	105	109	113	117	122	126	131	136	142
110	107	111	115	120	124	129	134	139	144	150	156
120	117	121	126	131	135	141	146	152	157	164	170
130	127	131	136	141	147	152	158	164	171	177	184
140	137	142	147	152	158	164	170	177	184	191	199
150	146	152	157	163	169	176	182	190	197	205	213
160	156	162	168	174	181	187	195	202	210	218	227
170	166	172	178	185	192	199	207	215	223	232	241
180	176	182	189	196	203	211	219	227	236	245	255
190	185	192	199	207	214	223	231	240	249	259	270
200	195	202	210	218	226	234	243	253	262	273	284
210	205	212	220	228	237	246	255	265	276	286	298
220	215	222	231	239	248	258	268	278	289	300	312
230	224	233	241	250	260	270	280	291	302	314	326
240	234	243	252	261	271	281	292	303	315	327	340
250	244	253	262	272	282	293	304	316	328	341	355
Stops											
0	0	0	0	0	0	0	0	0	0	0	0
10	10	10	10	9	9	9	8	8	8	7	7
20	21	20	19	18	18	17	16	16	15	15	14
30	31	30	29	28	27	26	25	24	23	22	21
40	41	40	38	37	35	34	33	32	30	29	28
50	51	49	48	46	44	43	41	40	38	37	35
Ascent Rate											
60	62	59	57	55	53	51	49	47	46	44	42

* Measured depth is not gauge depth. Table takes into account the effect of water density. The zero feet altitude column is for diving in a freshwater lake at sea level. According to Bell and Borgwardt (1976), these tables are theoretically correct (although they do not account for seasonal or daily barometric changes) but are still untested.

Adapted from Bell and Borgwardt (1976)

of 100 fsw (30.1 msw) places the diver in the F repetitive group (Appendix B). The no-decompression limit for a TOD of 80 fsw (24.4 msw) is 40 minutes (Appendix B). Therefore, the diver can have no more than 15 minutes of residual nitrogen time when starting the second dive; the diver is in the C repetitive group. To move from the F group to the C group requires 2 hours and 29 minutes.

A dive schedule for an altitude dive at 6000 feet (1829 m) would therefore be 80 fsw (24.4 msw) for 20 minutes, 2 hours and 29 minutes of surface interval time, followed by a 60-fsw (18.3 msw) dive for 25 minutes. In high-altitude diving, the last dive is often followed by a trip through mountain passes at an elevation higher than that used in the calculation. In this event, it is good practice to calculate the last dive as though it had taken place at the maximum elevation the diver will be passing through on the trip out.

10.12.5 Correction of Depth Gauges

Neither oil-filled nor capillary depth gauges provide accurate depth indications when used at altitude. Oil-filled depth gauges are designed to read 0 feet at a pressure of 1 ATA. At reduced atmospheric pressure, the gauge will read less than zero (unless there is a pin that stops the needle at zero); in the water, such a gauge will give a reading that is shallower than the actual depth. The depth readings can be corrected by adding a depth that is equal to the difference between the atmospheric pressure at the altitude site and 1 ATA. Table 10-3 shows mean atmospheric pressures

Table 10-3
Pressure Variations with Altitude

Altitude, ft	Pressure, mmHg	Pressure, psi	Pressure, atm*	Oil-filled gauge correction, ft
0	760.0	14.70	1.000	0
1000	732.9	14.17	0.964	1.22
2000	706.7	13.67	0.930	2.37
3000	681.2	13.17	0.896	3.53
4000	656.4	12.70	0.864	4.61
5000	632.4	12.23	0.832	5.70
6000	609.1	11.78	0.801	6.75
7000	586.5	11.35	0.772	7.73
8000	564.6	10.92	0.743	8.72
9000	543.3	10.51	0.715	9.67
10000	522.8	10.11	0.688	10.58
11000	502.8	9.73	0.662	11.47
12000	483.5	9.35	0.636	12.35
13000	464.8	8.99	0.612	13.16
14000	446.6	8.64	0.588	13.98
15000	429.1	8.31	0.565	14.76
16000	412.1	7.97	0.542	15.54
17000	395.7	7.66	0.521	16.25
18000	379.8	7.35	0.500	16.96
19000	364.4	7.04	0.479	17.67
20000	349.5	6.76	0.461	18.28

* U.S. standard atmosphere.

Source: NOAA (1979)

at various altitudes and the corrections necessary for oil-filled gauges.

Because of the reduced density of the air trapped in the capillary gauge at altitude, less water pressure is required than at sea level to compress the air to a given volume. As a result, the capillary gauge will indicate a depth greater than the actual depth. Because of the question about the accuracy of these gauges, a measured downline should be used.

10.12.6 Hypoxia During Altitude Diving

A diver surfacing from an altitude dive is moving from a breathing gas in which the oxygen partial pressure is relatively high to an atmosphere in which it is low. As a result, the diver may experience symptoms of hypoxia and breathing difficulty for a period after the dive (see Section 3.1.3.1).

10.13 NIGHT DIVING

Night diving exposes the diver to an entirely different aspect of the underwater world. Marine life may be more or less abundant and appear to be of different colors than is the case during the day. Areas that are familiar to the diver during the day may appear changed to the extent that orientation and locating familiar landmarks may be difficult even with good artificial light. Accordingly, special precautions and extra planning are required for night dives.

Anchoring is especially critical at night. The boat must be secure before the diver enters the water (except when liveboating, in which case other steps are appropriate (see Section 8.10.1)). It is also important at night to have correct marking lights that are clearly visible to other vessels in addition to a light the divers can see under water. A chemical light or small strobe light attached to the anchor line or downline is recommended.

Predive checks are particularly important at night, because the limited visibility precludes even a cursory inspection of equipment once in the water. Night diving in fog or heavy rain should be avoided because it is easy for the diver to lose sight of the lights on the dive boat or those carried by other divers.

Each diver should carry a reliable diving light with a charge sufficient to last longer than the time anticipated for the dive. A second light is advisable, because failure of lights is common. The light should be secured to the diver in a manner that permits the illumination of watches, gauges, or navigational aids. A chemical light should be taped to the snorkel or tank valve for underwater and surface visibility in case the dive lights fail. The entire night dive team should be careful to maintain dark adaptation before and during the dive (see Section 2.8.2). Every effort should be made to avoid shining diving lights directly into the eyes of crew members, both before and during the dive. Once in the water, it is easy to keep track of a buddy's light at night; however, one diver may occasionally lose another because the glare of the light being held prevents seeing the buddy's light. In this case, the divers should turn off or otherwise shield their lights momentarily, adjust their eyes, locate the buddy's light, and then immediately turn their lights back on.

If a team is left with only one light, the dive should be terminated. Lights may also be used to signal the surface; sweeping the light in a wide arc over the head is the standard 'pick me up' signal. At night, a whistle or chemical flare should also be carried in case of light failure.

Shore entries are more hazardous at night because such features as rocks, algae, holes, waves, and rip currents are not easily seen. Entries from boats, piers, and other surface platforms require special caution so that the diver avoids hitting objects on or below the surface.

If a shore exit requires a particular approach because of in-water obstacles, two shore lights in a line can serve as a navigational aid for divers. When possible, experienced night divers should be buddied with novice night divers. Making the entry at dusk rather than at night reduces some of the problems of night diving. Whenever possible, the area to be dived by night should first be dived by day to provide the divers with entry and exit experience.

NOTE

Decompression diving is more hazardous at night than during the day and should be avoided if possible. To be conducted safely, night decompression dives need considerable advance planning.

In night decompression diving, lights marking the decompression line are necessary to ensure that the divers conduct their in-water decompression near the dive boat or other platform. Divers operating in a decompression mode should not swim out of sight of lines or lights that will guide them back to the decompression line and dive platform.

10.14 DIVING IN DAMS AND RESERVOIRS

Hydroelectric dams across rivers in the northwest United States incorporate bypass and collection systems for the protection of migrating fish species such as salmon and steelhead trout (Figure 10-12). Because fish passage research is conducted at many of these dams, NOAA and other scientist/divers are often required to inspect, maintain, install, or retrieve research gear such as flow meters and fish guidance and passage devices. If time and circumstances permit, a shutdown and de-watering of turbine intakes, gatewells, and fish ladders is the safest and most efficient manner for performing work on dam bypass and collection facilities. However, safe and efficient diving operations can be performed within and on the upstream and downstream faces of dams even when these are still operating. The agency operating the dam supplies a diving inspector who coordinates such dives, because strict cooperation between the divers and the powerhouse operations staff is mandatory to ensure proper clearances for turbine shutdown and flow gate closures.

10.14.1 Diving at Dams

The safety aspects of diving at dams are comparable to those prevailing in cave, wreck, and over-bottom diving, and many of the same procedures are used in dam diving. Predive planning by the dive team with dam personnel will help to ensure a safe diving operation. If such operations are undertaken at altitudes in excess of 1000 feet, divers should take special precautions (see Section 10.12).

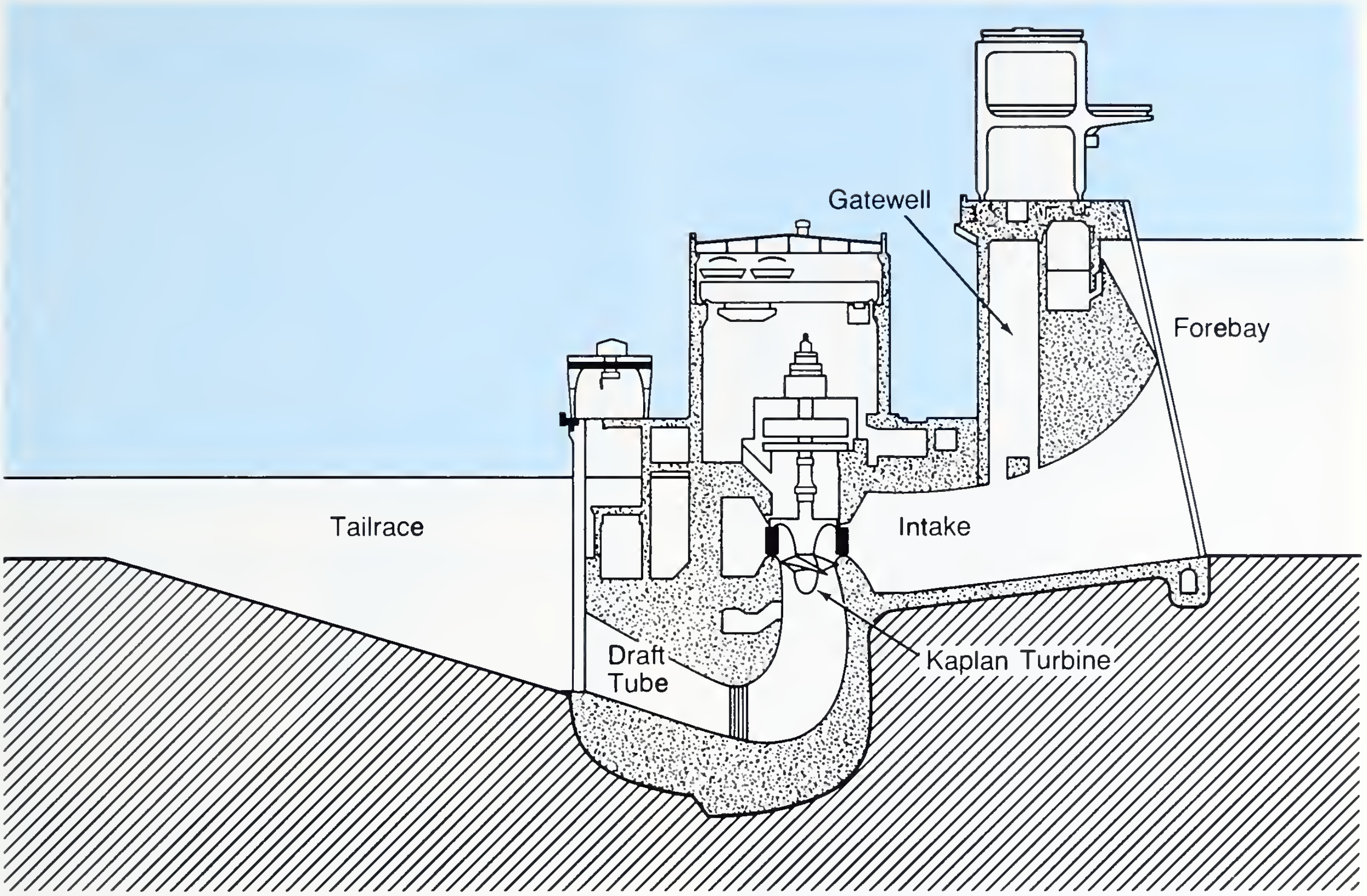
Three major conditions must be considered when planning dives at dams in the northwest (or any other) region:

(1) Water temperature
(2) Visibility
(3) Flow velocities.

Water temperatures may vary from slightly above freezing in winter to almost 80°F (27°C) in summer. Divers should be protected from the elements before diving and during surface intervals in both warm and cold seasons, because of the potential for heat exhaustion or hypothermia (see Section 10.8). Most research diving at dams occurs during the spring freshet, when rivers swell from rains and melting snow and fish migrations occur. The spring runoff produces low underwater visibility (e.g., 0-2 feet [0-0.6 m] in the Snake River) from silt carried by flooding waters. In warmer months, algae blooms may cause low underwater visibility. Even in clear water, the sediment disturbed by divers reduces visibility so that the small amount of natural light penetrating the gatewells is reduced. Although diving lights are only minimally effective, the problems associated with low visibility at dams can be overcome by careful planning, studies of the blueprints and plans of the dam, and familiarization with the research devices to be used during the dive. Objects can be recognized by touch and orientation maintained, even in zero underwater visibility, if the diver is familiar both with the gear and the dam's structures. The velocity of the flow and the force of the suction through screens or orifices at dams can be eliminated or controlled by coordinating the diver's actions carefully with dam operations personnel before the dive.

When bypass systems become fouled or clogged by river debris, divers sometimes are required to enter dam gatewells to clear the system's orifices. The hazards of gatewell diving can be reduced by taking adequate precautions to ensure that the influence of suction, caused by the large hydrostatic head, is avoided at the orifice. Variable-volume suits, which eliminate the need for buoyancy compensators, should be worn to avoid the danger of loose equipment becoming caught (see Section 5.4). Procedures are much the same as those for umbilical diving, whether the diver is using surface-supplied air or scuba cylinders. At a minimum, a tender line to the diver should be used for contact and signals, although hard wire communication is preferred. A diver cage should be provided to transport the diver to and from the orifice level and the

Figure 10-12
Cross Section of a Typical Hydroelectric Dam in the Northwestern United States



Courtesy George Swan

intake deck of the dam, and a safety diver is required. Figure 10-13 shows a diver ready to be lowered into a dam gatewell. Procedures to shut down the bypass system immediately in the event of an emergency should be coordinated with the dam operations controller before the dive.

Work on fish ladders (Figure 10-14) should be performed during off-season when the number of upstream adult fish runs is low and water flows can be cut off for a period of time, which permits the task to be completed in the open air. On rare occasions this is impractical, and diving is then the only way to complete the task. Flows in fish ladders appear quite turbulent when viewed from above; however, baffles or weir walls are regularly spaced perpendicularly to the flow, and the water flows either over the top of each weir or through large rectangular orifices located at the base of the baffle wall. When diving in pools between baffle walls, flows as high as 8.0 feet per second (fps) (2.4 mps) may be encountered in areas directly in line with the orifices but may be as low as 1.0 fps (0.3 mps) to either side or above the line of the orifice. By using safety lines and exercising caution, diving tasks may be performed in much the same manner as they are conducted when diving amid pools and boulders in rivers with relatively fast currents (see Section 10.15).

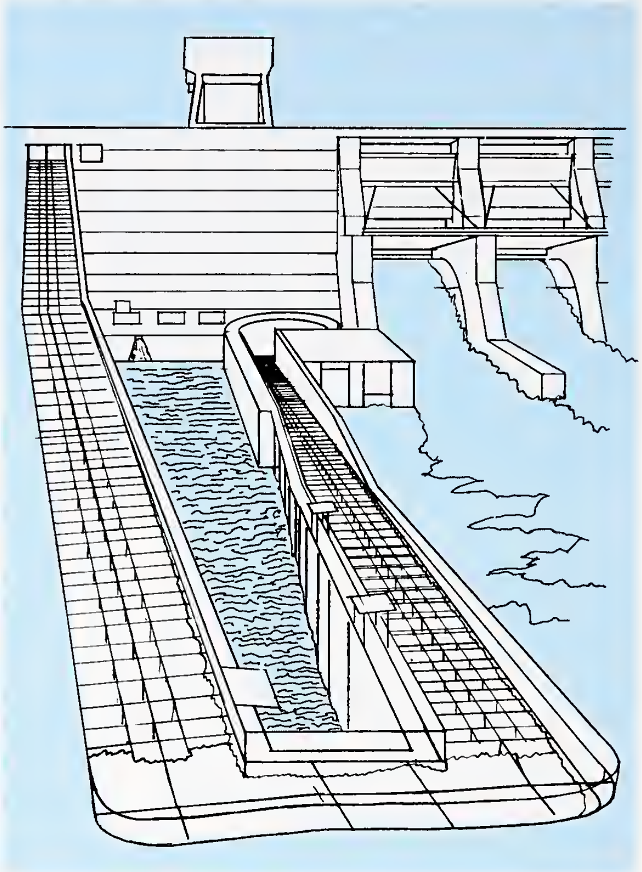
When diving tasks must be performed on the upstream face of a dam, turbines and/or spillway gates must be shut down. Adjacent units should also be shut down for safety and to reduce flows near the work station. Divers can be transported to and from the level of work and to the intake deck of the dam by means of a diver cage and crane. A boat or floating platform also is useful for the safety (standby) diver and equipment. Diving on the downstream face of a dam is handled similarly; flows are shut off to avoid sweeping the diver off station.

Divers should avoid water contaminants, such as spilled petroleum or lubrication products used in the routine operation and maintenance of dams or gaseous byproducts generated by underwater cutting and welding. These contaminants can become concentrated in confined areas such as gatewells, where the water level may be 15 to 20 feet (4.6 to 6.1 m) below the deck of the dam. Before starting or continuing a dive, any contaminant discovered should be eliminated from the dive site.

Figure 10-13
Diver Protected by Cage and Ready to be Lowered Into Dam Gatewell

Courtesy George Swan

Figure 10-14
A Fish Ladder at a Hydroelectric Dam in the Northwest



Courtesy George Swan

10.14.2 Diving at Water Withdrawal and Pumping Sites

The impact of water withdrawal on populations of juvenile fish in the Columbia Basin of the northwest United States is a major concern to fisheries agencies. Water is withdrawn from the Columbia and Snake Rivers via pumps and siphons and is then used for irrigation, industrial applications, drinking water, thermal cooling, fish and wildlife propagation, and other domestic needs. Before water can be withdrawn from these rivers, the U.S. Army Corps of Engineers requires those seeking permits to install and operate water withdrawals to install fish protective facilities. Periodically, divers are required to inspect fish screens at water withdrawal sites to monitor the condition of the screening and the status of compliance with established fish screening criteria.

Several basic types of water withdrawal sites are common: (1) a vaultlike structure with a screened underwater opening; (2) a pierlike structure set out from the shoreline that supports turbine pumps; (3) a combination pier/vault created by closing in the area under a pier with driven sheet piling or other material; and (4) a simple arrangement of a pump or siphon with a single intake line extending to a depth below the low water elevation. Some vaultlike structures may have trash rack bars in front of the fish screening.

A good and stable work boat serves as the best diving platform for accessing most withdrawal sites and expedites diver travel between sites, but divers should be careful when entering the water from a small boat. Some sites with enclosed fish screens must be accessed by ladder or small crane. For such a diving task, tanks, weight belts, masks, and fins are lowered by lines to the divers once they are in the water; this procedure is reversed after the dive.

Diving in and around pump intakes can be performed safely if certain hazards are recognized and the necessary precautions are taken. In general, intake velocities are not high enough to present a suction hazard, although pumps should be shut down, if possible. To perform an inspection during the pumping season, however, the approach velocities may have to be measured while the pumps are operating. Surface air supply hoses and safety lines should never be used when diving on sites with operating pumps unless the tender or another diver can tend the umbilical line to keep it away from the pump. Loose lines, hoses, straps, cylinder pressure gauges, and other gear should not be used or should be well secured to avoid being sucked into unscreened pumps or wound around impeller shafts. Because of the need for mobility in and around a pump site, a buddy team with scuba gear is the preferred method of diving at pump intakes. Low underwater visibility, ranging from 0-6 feet (0-1.8 m), is found in the lower Columbia and Snake Rivers, and this distance increases to 15 feet (4.6 m) in the upper Columbia River. If large pumps are operating and the visibility is exceptionally low, the dive should not be performed.

Divers should enter the water carefully with their feet first, because pump sites are notorious for the presence of debris, rocks, snags, and pieces of sharp metal, all of which present a hazard to divers, their suits, and any loose equipment. In addition, because there is less scuba diving activity in inland waters than in salt water areas, inland boaters tend to be less familiar with 'diver down' signal flags and their meaning. Pump site divers should descend and ascend close to the pump site structure or the shoreline. Surface personnel should watch for boating traffic and hail it with a loudspeaker to inform boaters that divers are operating under water. During the summer months, any activity conducted on or near the shoreline should be conducted cautiously because of the presence of rattlesnakes.

10.15 RIVER DIVING

Rivers throughout the world vary in size, turbidity, and in the terrain through which they flow; diving conditions vary with the river. Any river should be studied thoroughly and conditions known before the dive is planned. Log jams may be a hazard, as are submerged objects such as sharp rocks, trees, limbs, old cars, barbed wire, and the ever-present monofilament fishing lines, nets, and lures. Rapids or steep profiles are hazardous because a diver may be slammed against a rock or other submerged object and sustain serious injury or be held by the current.

River diving has a number of special aspects for which a diver should be prepared. For example, divers who grab the bottom to stop and look at an object should hold their face masks to prevent them from being torn off by the current. Divers should be aware that more weights are required when diving in currents than in quiet water, and they should plan their dives accordingly. Where there is considerable surface current, diving in large holes may be done by dropping directly to the bottom. At some distance below the surface, the diver may be surprised to find either no current or one flowing slightly toward the head of the hole. Divers should also remember when working with lines, tethers, or umbilicals in any type of current that the drag on these lines greatly hampers a diver's ability to travel and that the lines also create an entanglement hazard.

In a swift river current, entering the water can be difficult. One technique is to attach a line about 20 feet (6.1 m) long to the anchor with a handle (similar to those used by water skiers) on the other end. The diver can grasp the handle and descend by making appropriate changes in body position, which lets the current do most of the work. Descent can also be made by using the anchor line, but this requires considerably more effort. Divers always need something to hold onto because of the difficulty of moving across the bottom in fast currents. One helpful device is shown in Figure 10-15 (Gale 1977). This device, referred to as a creeper, is used by lifting and moving the corners forward in alternate turns, as shown; it can also serve as a diver's anchor when not in use. Large rocks or sharp drop-offs along river bottoms may create enough turbulence downstream to disorient a diver. In such a situation, the diver should move hand-over-hand along the bottom or use a creeper, because the current is less on the bottom. This technique can be used even on sand or gravel bottoms.

Another difficulty sometimes encountered in a fast-flowing stream or river is the blocking of light by bubbles. In or under white water, it may be almost dark. Rivers carrying large amounts of sediment, either normally or as a result of recent rains, are also extremely dark. Using underwater lights is not much help in turbid waters because the light is reflected or blocked by the particles suspended in the water. When working in rivers where the waters are reasonably clear but the bottom is easily stirred up, divers should work upstream against the flow. Any sediment that is disturbed will flow downstream, away from the direction of travel, which allows the diver to work in much greater visibility.

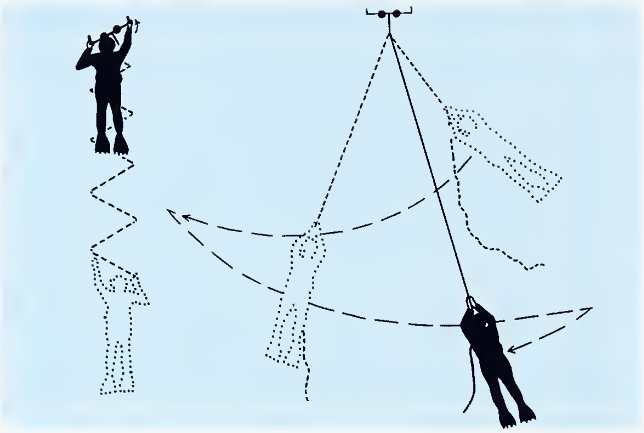
River diving near low-head dams presents additional hazards because the hydraulic action created by such dams creates currents with the potential to pull boats and swimmers back toward the dam from downstream (see Section 10.14.1). River divers required to work without lines in waters near low-head dams, waterfalls, or rapids with significant dropoffs should work on the bottom and as far clear of the affected area as possible.

Figure 10-15
Creeper—A Device Used to Move Across Rocky Substrates in Strong Currents

A. Closeup view

Photo William Gale

B. Creeper in use



Source: NOAA (1979)

10.16 DIVING FROM A SHIP

As in all diving operations, diving from a large ship requires comprehensive planning before the dive or series of dives. Because operating a ship represents a significant investment, all logistical factors involving personnel, equipment (diving and scientific), weather, etc., should be thoroughly considered in dive planning.

10.16.1 Personnel

When a ship is being used as a surface-support diving platform, the ship's captain has the final decision in any matter pertaining to the vessel. However, the dive master or senior diver has the final decision in any matter involving the divers. It is imperative that close communication between the dive master and the captain be initiated and maintained so that the intent of the diving operations is well understood and operations can be carried out as safely as possible.

It is highly desirable for the captain to have prior knowledge of diving techniques and procedures. Although this may not always be the case, a captain with such a background can add immeasurably to a diving operation's success. When diving from a ship, the following personnel requirements should be considered before beginning a cruise.

Dive master. Dive masters are responsible for all diving portions of the operation. These supervisors schedule all dives and designate divers and dive teams. They discuss the operational necessities of the dive with the captain and, as required, assist in carrying out these requirements (see Section 14.1.2.1).

Science coordinator. In conjunction with the dive master and the captain, the science coordinator formulates and ensures that the scientific goals of the diving mission are achieved. On a regular basis throughout the cruise, these goals are re-evaluated and, when necessary, re-directed (see Section 14.1.2.3).

10.16.2 Use and Storage of Diving and Related Equipment

A suitable diving locker should be designated and used for storing diving equipment. The designated area should be well ventilated, adequate in size, and equipped so that diving equipment can be hung up to dry. The diving locker should be kept locked when not in use, and the key should be kept by the dive master.

During predive planning, the stock of backup diving gear should be assessed. Equipment easily lost, such as knives, weight belts, etc., should be stocked in excess so that divers can be re-equipped quickly. Spare parts and replacements for critical life-support items such as regulators should be available on board.

Air compressors play an important role in a shipboard diving operation. The compressor should be positioned with intake toward the bow of the ship (the ship will swing into the wind while at anchor), away from the exhausts of main, auxiliary, or any other engines, and free of fume contamination from paint lockers, gasoline, and other solvents (or preservatives being used by diver/scientists). Cool running of the compressor requires good ventilation; in hot climates, the compressor should be run at night. When filling air cylinders, salt water from the ship's seawater system may be flushed over the tanks as a coolant. Oil-lubricated compressors should have some type of oil/water separator built into the system. It is also desirable to have a filtration column that eliminates CO, CO_2, hydrocarbons, oil, water, and other contaminants, in accordance with breathing air specifications (see Section 4.2).

10.16.3 Safety Considerations

When a large ship is selected for a diving platform, it is generally because the diving must be conducted a considerable distance from shore or in a remote region. When the distance is beyond the range of rapid emergency assistance or transport, the dive master should have preplanned procedures for prompt, adequate treatment on board ship and, when necessary, evacuation to a destination where further treatment can be obtained (see Section 19.7).

The dive master should contact all sources of emergency assistance and rapid transport close to the dive site and should determine the round-trip range of emergency transport vehicles, including the distances and times from shore to the dive site and back to the nearest recompression chamber.

On cruises out of the rapid emergency assistance or transport range, especially where decompression or repetitive diving is scheduled, a recompression chamber and a trained, qualified chamber operator should be on board ship. The possibility of decompression sickness, gas embolism, or an emergency free ascent requiring immediate surface recompression cannot be discounted. A portable double-lock chamber should be provided (see Section 6.1).

Safe execution of the dive also depends upon the proper handling of the mother ship before, during, and after the dive (Coale, Michaels, and Pinto, as cited in Heine 1985). Typically, any object remaining in one place for a period of time, such as sediment trap arrays, productivity arrays, or ships, will attract sharks. For this reason, open-ocean diving near such objects is not recommended. The bridge and the mess deck personnel should be told that no garbage can be dumped and no bilges can be pumped in the vicinity of the dive; fishing is also not permitted near the site. If the ship has been on station for some time before initiation of a dive, the ship should steam away from the station for a distance of at least 5 miles (8.0 km) so that the boat can be launched in cleaner water. To minimize the sonic attraction of sharks to the divers, the dive boat motor should be shut off and the mother vessel should be instructed not to come closer than 1/2 mile (0.8 km) to the dive location.

10.16.4 Using Surface-Supplied Equipment

All personnel, divers, and surface tenders should perform a thorough check of equipment. The ship's captain must be notified that divers are about to enter the water, and clearance should be obtained before the diving operation commences. The air supply system, helmet or mask, and communications should be checked to ensure they are functioning properly. If not, corrections must be made before the diver enters the water.

The water should be entered using a ladder. Jump entries are discouraged from heights more than 3 to 4 feet (about 1.0 m) above the water. A descent line should be used. Descent rate will depend on the diver; generally, however, it should not exceed 75 feet (22.9 m) per minute. If descending in a tideway or current, divers should keep their backs to the current so that they will be forced against the descent line (see Section 14.1.3.2).

Divers and surface tenders should review the line pull signals described in Section 8.1.4 thoroughly. Although voice is the primary means of communication between divers and surface tenders when surface-supplied equipment is used, pull line signals are the backup form of communication if the voice system fails.

When the bottom is reached, the surface tender should be notified and the diver should proceed to the work site. The surface tender also should keep the diver constantly informed of bottom time. The diver should always be notified a few minutes in advance of termination time so that there is time to complete the task and prepare for ascent.

When work is completed, the diver should return to the ascent line and signal the surface tender that he or she is ready for ascent. The surface tender should pull in the excess umbilical line slowly and steadily. The diver should not release the ascent line but may assist the tender by climbing the line. The surface tender or dive master must inform the diver of his or her decompression requirements well in advance of dive termination. A diving stage may be required for long decompressions. When decompression is completed, the diver should return on board ship via the ladder or diving stage, receiving assistance from the surface tenders as required.

10.16.5 While Underway

Diving while underway is not widely practiced and can clearly be dangerous. However, divers may occasionally be required to dive from a ship that is underway to perform work or to make underwater observations that cannot be made from a stationary platform or surface. Because this type of operation is inherently more dangerous than other diving operations, it should be done only when no safer alternative exists. Strict compliance with certain rules is mandatory.

Only self-contained diving equipment should be used when entering the water from a moving ship. Although special requirements may dictate higher speeds, the ship should proceed if possible at speeds under 3 knots (1.6 m/s). The use of a small boat, manned continuously while divers are in the water, is required.

It is essential that great care be taken when entering the water from a moving ship. A spot should be selected on the side of the ship well aft and, if possible, aft of the ship's propeller(s). The diver should never enter the water directly off the stern, because propellers and the ship's movement through the water cause turbulence that could buffet a diver severely or damage or tear off equipment.

The step-in method (see Section 10.4.1) is recommended for entry from a moving ship. This allows maximum distance between the side of the ship and the point of entry. Caution should be exercised in using the step-in method when the deck of the ship is high off the water surface.

Most dives from a ship underway require the ship to tow equipment (trawls, sleds, etc.) that the diver will use during the dive. This equipment may be on the surface, partially submerged, or submerged. The small boat should maintain position behind and just to the side of the towed equipment. Divers should enter the water in succession; the interval between entries should be long enough to avoid having the divers collide with each other but short enough to prevent the divers from being too widely separated in the water.

Divers should drift back and maintain visual or hand contact with the cable being used by the ship to tow the equipment. They should work their way back along the cable until the equipment is reached, descending as required.

Hazards and diver difficulties increase if active nets or their components are moving at great speed. During the early retrieval of purse seines, the net components (web, purse rings, and purseline) move slowly. Toward the end of the pursing and net-retrieving sequence, however, these components move through the water quickly. Since divers usually lack communication with surface winch and line hauler operators, the divers must stay out of the bight of the line or the immediate path of the gear.

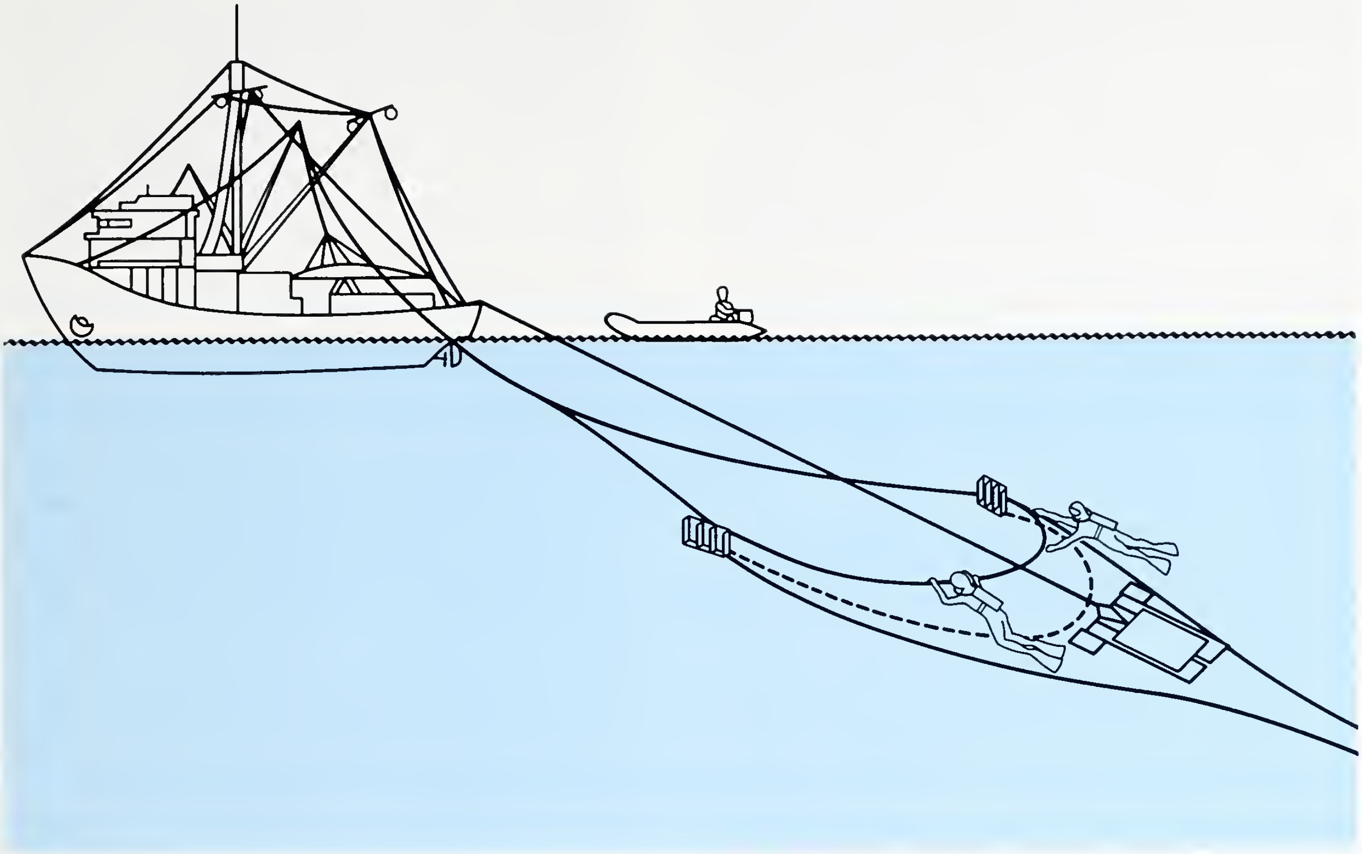
Diving within the influence of a trawl or other device towed from vessels under way is hazardous. The hazards include entrapment within the net, fouling, and being forced against bottom obstructions. If the device is moving slowly (under 1.5 knots; 0.8 m/s), the diver may be able to swim alongside for short periods. At speeds up to about 2.5 knots (1.3 m/s), divers may hold onto large nets without seriously distorting them. Both of these methods require the diver to be in excellent physical condition and to be trained in this special form of research diving. Scientists who plan to dive near capturing systems should undertake special training dives that simulate conditions likely to be encountered.

High (1967) and Wickham and Watson (1976) described methods used by divers to observe trawls. Fishing gear researchers operating in relatively deep waters off the northwestern coast of the United States on large midwater or bottom trawls generally descend to the trawl by entering the water from the towing vessel and moving down the towing cables. Care must be exercised to avoid jamming broken cable strands into the diver's hand. This descent technique provides a direct route to the net and expends a minimum of energy and compressed air. Caution must be observed as the divers approach the turbulent water behind the otterboards, especially when the boards are in contact with the bottom. Clouds of sediment stirred up by the otterboard obscure portions of the bridles between the otterboard and the net, so divers must feel their way along the bridle. As an alternative, when horizontal visibility is as much as 25 feet (7.6 m), experienced divers may swim inboard of the otterboard just within the path of the oncoming trawl and wait for the bridles to clear the mud cloud or for the net to appear.

When this type of trawl diving is conducted, a safety pickup boat is required. The boat is operated on a parallel course adjacent to the estimated position of the trawl and divers. At the termination of the dive, the buddy team makes a normal ascent and is picked up by the boat.

In the shallow waters available for fishing gear research in the southeastern United States, a two-place diver sled is used to transport divers to and from the trawl. The dive sled, which is towed behind the vessel towing the trawl, is positioned above and slightly behind the trawl's headrope. The divers are transported in a small support boat and are positioned well ahead of the sled close to the downwind side of the sled towrope. When the divers are ready to enter the water, the support boat is turned away from the towrope, and the motor is taken out of gear. Once the divers are in the water and clear of the propeller, the support boat motor is placed in gear, and the support boat moves to a position slightly behind and to the downwind side of the sled. The divers position themselves 20 to 30 feet (about 6 m) apart along opposite sides of the towline. The pilot takes the lead position facing the port side of the sled. When the sled reaches the pilot, he or she grabs the passing control surface or sled frame and trails back to a parallel position with the sled. From this position, the pilot slides aboard the sled and assumes a prone position at the controls. The observer boards the sled in the same manner but from the opposite side. When the

Figure 10-16
Support Ship, Trawl, Diver Sled, and Support Boat



Adapted from Wickham and Watson (1976)

divers are positioned, the pilot releases the dive control restraints and takes control of the sled. The divers descend to the trawl and, depending on the size of the trawl or the purpose of the dive, observe it from the sled or land the sled on the trawl and tie it to the trawl webbing (Figure 10-16). With the sled tied off, both divers can leave the sled to conduct their work on the trawl. At the end of the dive, the divers reboard the sled, release the tie downs, and ascend to the surface. The support boat then moves to the sled, and, on a signal from the pilot, the motor is taken out of gear. The divers kick free of the sled and swim over to board the support boat.

When using a dive sled, divers must be particularly careful to maintain proper breathing rhythms to prevent an embolism from occurring if the dive sled rises suddenly on a wave. The pilot should have a depth gauge mounted so that it can be read easily at all times and should continually monitor the gauge, maintaining a constant depth or making any necessary depth changes slowly. A dive sled also facilitates the use of a hardwire communications system between divers and the surface, which increases the safety and efficiency of trawl diving operations.

Divers making observations while hanging directly onto the trawl can move to different parts of the trawl by pulling themselves hand-over-hand. However, trawls having a stretched mesh size of less than 2 inches (about 5 cm) (i.e., each side of the aperture about 1 inch long) are difficult to hang onto and may necessitate the use of hand-held hooks to enable the divers to move about.

By using a separate towline for the divers, small trawls and other moving gear can be observed without direct contact, which might affect the system. A dive sled can also be used for this purpose and, with the addition of a current-deflecting shield, will provide more protection for divers than is possible for divers hanging directly onto the gear.

Trawl divers must be alert to possible dangers in the bottom trawl's path. Some underwater obstructions may cause the trawl to stop momentarily and then to surge ahead with great force. Large objects may be lifted and carried into or over the net. Turbulence behind the otterboards may lift sharp-spined animals up off the bottom and into the path of the divers. If any of the diver's extremities get ahead of the bottom trawl, the diver is in imminent danger, because severe injury would result from being pinned between parts of the net and an obstruction.

Jellyfish present a hazard to trawl divers and can seriously reduce their ability to function safely under water. When jellyfish are abundant, it is impossible for towed divers to avoid contact with them. The problem increases when jellyfish are strained through the trawl's webbing, which causes the divers to be showered with hundreds of jellyfish pieces. To avoid being stung, trawl divers must dress in full-length wet suits (1/8 in. (0.3 cm) thick in warm water), hoods, gloves, boots, and full-face masks whenever large numbers of jellyfish are in the vicinity.

In the event divers are carried into a trawl from which they cannot readily extricate themselves, they must cut an exit through the web. Since trawls usually have heavier web in the aft portion (cod end), an escape should be cut forward in the top of the trawl body and a 3 foot (0.9 m) long diagonal slit should be made in the trawl. Another similar slit should be made at 90 degrees to and beginning at the upstream end of the first slit. The water current should then fold a triangular flap of webbing back out of the way, leaving a triangular escape hole. The diver's buddy should assist the trapped diver through the opening to free any gear that snags on meshes. Often an additional small single-blade knife is carried in an accessible place such as the forearm.

WARNING

Divers Working Around Trawls Must Carry a Sharp Knife Strapped to the Inside of the Calf or Forearm to Prevent Its Catching on the Web

Vessel course or speed changes normally pose no hazard to working divers. Often, changing speed can be used as a simple signal between divers and vessel personnel. As speeds rise above 2.5 knots (1.3 m/s), divers will have difficulty holding their mouthpieces in and keeping their face masks on. At higher speeds they may lose their grip and be forced off the net. When stopped, the net settles slowly, becoming slack gradually rather than suddenly. In this situation, the divers should be cautious of a sudden start, which may tangle them in a line or web. Divers working from a sea sled adjacent to a trawl may be forced against the trawl during a turn. Trawl divers should be well-trained so that they will know where they are in relation to any part of the trawl at all times, even when only a small portion of the net is visible in turbid waters.

To determine gear efficiency, it is necessary to measure trawls under tow. A number of measuring tools have been adapted or designed specifically for measuring trawls. The measuring tools selected to use when studying a trawl will depend on the size of the trawl and the degree of accuracy required. An estimate of the distance between two points on a trawl can be made by pulling low-stretch polypropylene twine taut between the points and then cutting the line. The tied end will remain with the trawl until retrieval, when the line can be removed and measured. To measure more accurately the horizontal spread of a trawl (the distance from wing to wing across the mouth of a trawl), a 1/8 inch (0.3 cm) in diameter stainless steel cable marked in 1 foot (0.3 m) increments is used. The cable is stretched across the mouth of the trawl, with one end attached to the first hanging on one wing and the other cable end pulled through a small pulley attached to the first hanging on the opposite wing. The cable is pulled taut across the net by one diver, while the other diver records the spread reading. The vertical opening (the distance between the trawl headrope and footrope) on small trawls is measured with a fiberglass measuring rod marked in 6 inch (15.2 cm) increments. On larger trawls, the vertical opening is measured with a calibrated depth gauge. Short distance measurements can be made accurately with a fiberglass tape measure. Trawl door measurements are made with an inclinometer for door tilt and a door angle measuring device for door angle of attack.

Equipment for Diving While Under Way. Special attention must be given to diving equipment used during dives on moving gear. Single-hose regulators with large-diameter purge buttons occasionally free flow when used during underway diving because of the strong water current being exerted against the face of the button.

Reserve valve pull rods are the single greatest source of diver entanglement in webbing. K-valves in combination with submersible pressure gauges are generally safer for use in trawl diving; however, if J-valves are used, the following information is important. When a pull rod is used, the pull-ring should be brazed shut or taped to prevent webbing from slipping into the loop. Submersible pressure gauges permit team members to monitor each other's air supply and depart the net while ample air reserve remains. The strap on the pressure gauge hose should be fastened to a strap of the backpack only. If the gauge is left dangling at the diver's side, it may become caught in the net.

Adjustable straps on face masks and fins are an occasional source of difficulty for trawl divers. The loose ends of the fin straps should be on the inside of the strap next to the ankle to prevent the flopping strap or buckle from entangling in the net. Straps should be adjusted until comfortable and then securely taped in place to prevent pulling out.

Towed divers must have exposure suits with warmth qualities superior to those necessary during regular dives. Rapid movement through cold waters will quickly chill divers, reducing their effectiveness and exposing them to the dangers of hypothermia (see Section 3.4). Variable-volume dry suits are excellent for use in water temperatures below 60°F (16°C); however, additional drag on a towed diver may preclude the use of these suits when high mobility is desired.

Snorkels should not be attached to a towed diver's mask. Generally, snorkels are omitted from the gear complement because of their tendency to catch on webbing. They are not normally needed because the diver is on the surface only for a short period before being picked up by a safety boat. Divers are advised to carry signal flares under conditions where it may be difficult for the boat to locate the diver after surfacing.

SECTION 11
POLLUTED-WATER DIVING

POLLUTED-WATER DIVING

11

11.0 GENERAL

NOAA divers, commercial divers, and scientific divers have all been called on in recent years to perform working dives in waters contaminated by a variety of pollutants, including pathogenic micro-organisms, toxic chemicals, and nuclear reactor effluents. Research is continuing on the specific hazards and effects on diver safety and health of these occupational exposures and on the development of equipment and methods of protecting divers from such hazards.

Because water pollution is so widespread, all divers should be aware of the hazards of polluted-water diving. They should also be familiar with the pre- and post-dive procedures, equipment requirements, and medical surveillance activities appropriate for polluted-water diving.

11.1 MICROBIAL HAZARDS

Microbial pathogens—bacteria, viruses, parasites, protozoa, fungi, and algae—may occur as part of the natural environment or be introduced into the aquatic environment through an external source, such as sewage or chemical wastes from industrial sources, commercial ships, or agricultural run-off. These wastes are often carried into the ocean by rivers and streams; although contaminants are diluted by the ocean, they can continue to have a powerful effect on water quality and the diver's environment. In addition, pollutants may "clump" together to form discrete and highly toxic parcels of contaminated water. Divers may be exposed to waters polluted by microbes in a variety of occupational settings: when they clean or paint ship hulls in polluted rivers or harbors, monitor ocean sewage dump sites, or perform scientific dives to observe the behavior of marine life in lakes, rivers, or coastal waters. NOAA divers are most likely to be exposed to hazardous contaminants during dives near or on the soft bottom sediments, which provide ideal environments for accumulating contaminants and encouraging microbial growth (Phoel 1981).

11.1.1 Health Effects of Exposure to Microbial Hazards

The number and kinds of pathogenic organisms that may be present in polluted water are many. To date, the following organisms have been implicated as potential hazards to the health of divers swimming in polluted water: several bacterial species, including *Vibrio, Escherichia, Legionella, Actinomycetes, Aeromonas, Salmonella, Shigella, Enterobacter, Klebsiella, Pseudomonas,* and *Staphylococcus;* viruses; protozoa; molds; fungi; algae; and parasites belonging to other families (Colwell and Grimes 1983).

WARNING

Before Diving in Potentially Polluted Waters, Divers Should Sample the Water for the Presence of Pathogens or Other Contaminants or Obtain Such Information From Reliable Sources

Divers working in waters contaminated or infested with these organisms may be subject to a variety of maladies, including:

- ear infections
- eye infections
- respiratory tract infections
- inflammation of the intestinal tract
- warts
- skin infections
- parasitic infections
- central nervous system effects
- systemic or pulmonary fungus infections.

Because the signs and symptoms of many of these conditions do not manifest themselves for a period of hours to weeks after the dive, it is often difficult to associate the polluted-water exposure with the resulting symptoms. Although personal hygiene and specific preventive measures can counteract some of these effects, the surest methods of protecting divers operating in microbially contaminated waters are to isolate them completely from contact with these organisms and to ensure that divers are adequately decontaminated after completion of the dive. Section 11.4 describes protective equipment and procedures designed to achieve these goals.

11.1.2 Factors Affecting Microbial Pathogenicity

Recent research efforts have identified several factors that affect the pathogenicity and virulence of the microbes found in polluted water (Colwell 1982). Concentrations of heavy metals, such as those associated with waste petroleum products, may reduce species diversity in a manner that favors pathogenic species; changes in water temperature or salinity may also have similar effects. Altering the levels of certain nutrients in the water may operate to select out non-pathogenic species and thus permit pathogens to thrive. The ability of some organisms to stick or attach themselves to surfaces, including a diver's skin and mucosa or his equipment, makes them persistent threats. Seasonality also affects the distribution of many species of microbes, and divers are generally at greater risk of incurring microbial infections during the summer months or when diving in warm water.

11.2 CHEMICAL HAZARDS

As many as 15,000 chemical spills are estimated to occur in U.S. waterways every year, and countless other chemical-laden discharges take place regularly as industrial and municipal facilities expel their wastes into lakes, rivers, and coastal waters (McClellan 1982). Divers operating in waters contaminated by chemicals, many of which are toxic, have experienced upper respiratory tract infections, difficulty in breathing, skin reactions, nausea, burns, severe allergic reactions, and tingling of the limbs. As in the case of microbial hazards, it may be difficult to relate cause and effect.

Industrial chemicals commonly found in polluted water include:

- phosphates
- chlorates
- peroxides
- acids
- solvents (benzene, xylene, toluene).

Petroleum and petroleum products are the most common chemical hazards encountered by divers, because these substances are frequently spilled in incidents involving commercial vessels or in other marine accidents, such as oilwell blowouts and spills from storage facilities. Divers may be called on to help with spill cleanup and must wear carefully selected gear during such operations because oil destroys neoprene and rubber (Figure 11-1). In addition, the solvents and other chemical substances used to clean up spills permeate many types of protective clothing and can cause either gradual or catastrophic deterioration of other materials. It is important not to wear the same equipment in successive dives involving incompatible chemicals, because diving equipment may absorb enough of the first chemical or chemicals to cause a reaction on subsequent contact with an incompatible substance.

Figure 11-1
Diver Working in Contaminated Water

Photo: Steven M. Barsky, Courtesy Diving Systems International

Chemical and petroleum-product spills occur as a result of vessel collisions and groundings, oilwell blowouts, major storage facility releases, and illegal dumping of toxic or hazardous wastes. The Environmental Protection Agency (EPA), the U.S. Coast Guard, and NOAA all have important roles to play in emergency response and environmental assessment.

The steps involved in protecting the health and safety of divers and other personnel (and the health of the public and the environment) responding to a spill emergency include:

- identifying the hazardous substance(s) present
- evaluating the hazard associated with these substances
- ameliorating the effects of the release.

Field samplers are used to take grab samples of the contaminated water as close to the source of the contamination as possible. On-site portable "laboratories" can often be used to analyze these samples. Results of sampling are useful in selecting the appropriate level of protective equipment and clothing needed by response personnel, measuring the extent of the potential environmental impact of the spill, and determining the necessary cleanup procedures.

11.3 THERMAL HAZARDS

Overheating of the diver, or hyperthermia, may be a critical factor for divers working in tropical waters or in the heated environment typical of cooling water outfalls or nuclear reactor pools. The temperature of the water in the cooling pools surrounding nuclear reactors and in the canals at facilities that generate nuclear power may reach 110-120°F (43-49°C). Divers performing maintenance and repair tasks in these superheated waters must be specially trained in safety and emergency procedures and be protected from hyperthermic stress; in addition, since biological sampling has shown that pathogenic organisms are often present in these waters, divers must also be isolated from microbial hazards.

Overheating can become acute even when divers are working in polluted-water environments at moderate temperatures (82°F or 28°C), because the divers are in effect encapsulated in their diving suits. In addition, the need to remain suited-up during the often-lengthy decontamination period after a polluted-water dive adds to the overheating problem, because divers' body temperatures will continue to rise throughout this post-dive period (Wells 1986).

The threat posed by hyperthermia is increased by the fact that divers are generally unaware of the extent of their own overheating. For example, many divers do not exhibit the signs or symptoms of hyperthermia until after their core temperatures have risen to a level that is considered medically unsafe. Thermal monitoring is thus highly recommended for divers working in warm polluted waters.

11.4 EQUIPMENT FOR POLLUTED-WATER DIVING

Divers who must dive or work in contaminated waters should choose their equipment with a view toward maximum protection. When selecting equipment, divers must consider such factors as the degree and extent of the contamination, the duration of the exposure, and the type of contamination they will be dealing with—biological, chemical, or thermal. Other factors to be considered when selecting equipment include the geographic area in which the dive will take place, the space available for set-up operations, and the cost-effectiveness of various types of equipment. This latter consideration may be particularly important if the contaminated equipment will have to be disposed of after use.

11.4.1 Self-Contained Underwater Breathing Apparatus

Standard scuba gear offers inadequate protection to divers operating in contaminated water environments. When scuba is used, the diver's mouth is directly exposed to the water, and the process of inhalation introduces droplets of water into a diver's respiratory tract. Scuba divers who are wearing a dry suit and full-face mask mated to a second-stage regulator can be exposed via inhalation, ingestion, and skin contact (at the neck, hands, etc.). Thus, even hybrid scuba equipment arrangements often provide grossly inadequate protection. However, an extended series of tests performed by NOAA has succeeded in identifying a suit-and-mask system that can be used by scuba divers required to dive in biologically (and in some cases chemically) contaminated waters. NOAA considers this scuba system the best protection currently available, but research to identify and develop a better system continues.

The recommended system consists of a "smooth-skin" dry suit with an attached hood and boots. Because neoprene material acts as a sponge and degrades when in contact with chemicals, suits of this substance cannot be used in contaminated water. The seams of the suit selected should be sealed by vulcanization or a similar procedure. The number of openings in the suit should be minimized to reduce the number of potential failure points. Requiring boots to be attached to the suit permits the number of openings to be reduced to 3 or 4, depending on whether or not the suit is of the neck-entry or shoulder-entry type. Because many neck-entry suits are not compatible with the types of helmet appropriate in this kind of diving, most polluted-water suits will be of the shoulder-entry type. The gloves and helmet should be attached to the suit via positive locking mechanisms, and heavy-duty zippers should be used for the shoulder opening. Because gloves are the weakest point in the suit systems used in polluted-water diving, they should be selected carefully, with consideration given to compatibility of material with the chemicals encountered and resistance of the glove material to puncture and stress. The boots chosen for the scuba suit system should be made of a thick, smooth material that is resistant to abrasion and punctures, have a nonslip sole, and be designed to accommodate fins (Pegnato 1986).

The suit must be inflatable either by means of the diver's air tanks or a pony bottle. The suit must also have a diver-controllable exhaust valve to keep water out of the suit. The hood must have an installed relief valve that automatically vents any air that accumulates in the hood, and the skirt surrounding the face must have a smooth outer surface. Figure 11-2 shows a diver wearing a Viking dry suit, with a Draeger hood attached via a neck ring.

The mask to be used with this suit system must be internally pressurized to prevent the inward leaking of the contaminated water. Such a mask offers polluted-water divers a considerable increase in protection over other masks, because it provides full face coverage, separate air intake and exhaust ports, and a positive interior pressure that seats and seals the mask skirt against the diver's hood (Pegnato 1986). The mask can be coupled with any top-rated standard first-stage regulator; the regulator's secondary output pressure must be freeze-protected and provide an intermediate pressure that is compatible with the second stage. Before attempting a dive in polluted water with this system, divers should make a test dive in clean water to ensure that the diver remains completely dry. Because many of these systems use more air than the standard scuba system, predive planning must take this need for additional air into account (Pegnato 1986).

WARNING

Divers Operating on Compressed Air Near Spill Sites Should Use Bottled Air Compressed in a Clean Atmosphere To Avoid the Danger of Contaminated Compressor Air

11.4.2 Surface-Supplied Diving Equipment

To achieve the degree of protection necessary for surface-supplied diving in polluted water, several modifications to existing surface-supported diving systems are necessary. For example, a series exhaust valve (SEV) that consists of two exhaust valves aligned in series has been designed to overcome the problem of "splashback" through the exhaust valve of a demand regulator. Several commercially available helmets and masks now incorporate this NOAA-designed SEV feature.

Figure 11-2
Diver in Dry Suit

Photo: NOAA Diving Program

The "suit-under-suit" (SUS) concept was developed by NOAA, in conjunction with the Environmental Protection Agency, the Coast Guard, and the Department of Energy, to solve two of the most significant problems of polluted-water diving: thermoregulation and suit leakage. The SUS has two layers: a thin, foam, neck-entry inner dry suit layer with attached booties, and an outer layer that consists of a dry suit with ankle exhaust valves. An adjustable-pressure, arm-mounted exhaust valve is worn over the inner suit, and a "neck dam" installed in the outer suit is clamped to the entrance yoke of the inner suit and thus creates a closed cavity between the two suits. Figure 11-3 shows a drawing of the SUS.

Clean water is pumped into the cavity between the two layers of the SUS; the water can be hot or cold, depending on whether the diver will need cooling or heating during the dive. The working temperature range for the SUS appears to be from 30 to 130°F (-1.1 to 54.4°C), allowing divers to perform rescues in freezing waters or to work in the cooling pools of nuclear power facilities. Since the entire volume of the SUS is filled with water under a pressure slightly greater than the pressure of the ambient water, any leak in the suit will result in clean water from the suit leaking out into the polluted water, rather than polluted water entering

Figure 11-3
NOAA-Developed Suit-Under-Suit (SUS) System

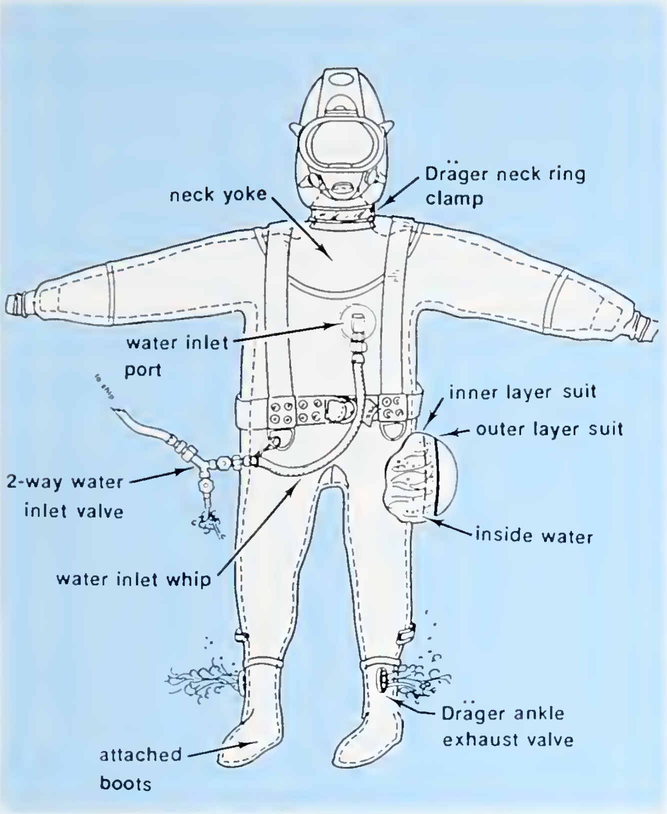


Photo: NOAA Diving Program

the suit. The SUS thus provides protection against microbial, thermal, petrochemical, and chemical diving hazards (Pegnato 1986).

Another system that is appropriate for polluted-water diving is the traditional hard-hat diving rig, consisting of built-in or attachable gloves and a suit mated to a breastplate or to a breach ring mated to the helmet. The entire hard-hat unit is waterproof and provides complete protection unless the suit develops a tear or leak.

11.4.3 Polluted-Water Diving Procedures and Precautions

Divers required to work in polluted waters must rigorously observe a series of procedures designed to provide maximum protection of the diver and the support crew. In addition to the careful selection of suits and helmets, divers and support crew members must be specially trained in the hazards of polluted-water diving. Figure 11-4 shows NOAA support personnel preparing a diver for a polluted-water dive. Careful records must also be maintained of the types of contaminants divers are exposed to, e.g., names of chemicals, types of pathogens, etc. Equipment used in contaminated water must be maintained, repaired, and replaced more frequently than equipment used in unpolluted environments.

Figure 11-4
Dressing a Diver for Contaminated-Water Diving

Photo: Steven M. Barsky, Courtesy Diving Systems International

11.4.3.1 Decontamination Procedures

Both divers and tenders must go through a decontamination process after completing a dive in contaminated water, because evidence shows that divers infected with microbes can contaminate their suits and thus spread infection or reinfect themselves unless the suit is adequately decontaminated. Suits badly contaminated with radiation from reactor pool diving must be discarded and disposed of properly. Figure 11-5 shows a polluted-water decontamination team decontaminating a diver after a polluted-water dive. Team members are wearing decontamination protective equipment, and the diver is wearing a MK12 helmet and polluted-water diving suit. After each dive, the diver is sprayed with a high-pressure sprayer; three separate spraying solutions are often used. The first involves a

Figure 11-5
Decontamination Team at Work

Source: NOAA Diving Program

neutralizing agent or disinfectant appropriate for the particular contaminant, the second consists of a detergent washdown, and the third and final spray is a fresh-water rinse. If contamination is severe, heavy-duty brushes can be used to scrub the zippers, helmet locking mechanism, boots, boot soles, and seams of the suit system. The entire decontamination process should be as thorough as possible, but it is important to remember that time is important because the diver remains effectively encapsulated throughout the procedure and is thus subject to hyperthermia (Wells 1986).

11.4.3.2 Medical Precautions

Divers who work in polluted waters should be given baseline and annual physical examinations. Physicians administering these examinations should pay particular attention to the respiratory and gastrointestinal systems and to the ears and skin. Any polluted-water diving guidelines recommended by NOAA, the Environmental Protection Agency, the National Institute for Occupational Safety and Health, or the Occupational Safety and Health Administration should be observed. Individuals with open cuts should not dive in microbially polluted waters. In addition, divers must maintain current immunizations for diphtheria, tetanus, smallpox, and typhoid fever, and they should clean their ears carefully with otic solution immediately after any dive in polluted water. This ear-cleaning procedure has proven to be dramatically effective in reducing the incidence of otitis externa associated with polluted-water diving.

SECTION 12
HAZARDOUS AQUATIC ANIMALS

HAZARDOUS AQUATIC ANIMALS 12

12.0 GENERAL

Many aquatic animals are potentially hazardous to divers. Although only a few present serious physical threats, the damage inflicted by others can seriously impair a diver's effectiveness. The material that follows discusses some of these animals. For convenience, hazardous aquatic animals have been classified as:

- those that abrade, lacerate, or puncture
- those that sting
- those that bite
- those that shock
- those that are poisonous to eat.

This classification has limitations: the categories overlap, and, although most hazardous species fall neatly into one or another, some of the classifications are arbitrary.

For a discussion of the treatment of injuries inflicted by hazardous aquatic organisms, see Section 18.

12.1 ANIMALS THAT ABRADE, LACERATE, OR PUNCTURE

The bodies of many aquatic animals are enclosed in sharp, pointed, or abrasive armor that can wound the exposed areas of a diver's body that come into forceful contact with these creatures. Included in this group of animals are such forms as **mussels, barnacles, sea urchins,** and **stony corals** (Figure 12-1). The wounding effect of contact between these animals and humans is intensified in aquatic habitats because human skin is softened by water. Although single encounters of this sort are unlikely to produce serious injury, repeated encounters during extended diving operations can produce multiple injuries that may become problems. Wounds continuously exposed to water resist healing, and careless divers may in time be incapacitated by an accumulation of ulcerated sores. Wounds are especially likely to be aggravated when working in the tropics. To compound the problem, secondary infections in such wounds are not uncommon. Thus, long-term diving projects can be crippled if participants fail to avoid these injuries, minor though they may initially seem.

Figure 12-1
Sea Urchin *Echinothrix diadema* on a Hawaiian Reef

Photo Tony Chess

12.2 ANIMALS THAT STING—VENOMOUS MARINE ANIMALS

A diverse array of otherwise unrelated animals is considered together in this section because their ability to inject venom into other organisms poses a threat to divers in the water. The instrument of injection varies from the stinging cells of the coelenterates (hydroids, corals, anemones, and jellyfishes) to the spines on the bodies of crown-of-thorns starfish, sea urchins and fishes, radular teeth of cone shells, beaks of octopuses, bristles of annelid worms, and the fangs of snakes. Mere contact with the surface of some sponges can produce a severe dermatitis. The toxicity of the venom, as well as the amount of venom introduced, varies from one species to another and sometimes among individuals of the same species. Furthermore, humans may differ in their sensitivity to a given venom. The reactions of humans to marine animal stings may range from no noticeable reaction to mild irritation to sudden death. It is wise to become informed about and to avoid all marine organisms known to be venomous; occasional contact is inevitable, however, for even the most experienced divers.

12.2.1 Hydroids, Jellyfishes, Sea Anemones, and Corals

Grouped here are a variety of organisms that drift or swim slowly at the water's surface or at mid-depths.

They have gelatinous, semi-transparent, and often bell-shaped bodies from which trail tentacles armed with stinging cells, called nematocysts. In large specimens, these stinging tentacles may trail down as much as 100 feet into the water.

Nematocysts are characteristic of a large group of related, though superficially very diverse, marine animals known as **coelenterates.** In addition to the jellyfishes, the coelenterates also include the hydroids and stinging corals, considered below. Different coelenterates have different types of nematocysts, but all function similarly. When the animal is disturbed, the nematocyst forcefully discharges a venomous thread that, in some species, can penetrate human skin. The reactions of humans to the stings of hazardous coelenterates range from mild irritation to death.

Stinging hydroids occur on many reefs in tropical and temperate-zone seas. Typically, they are featherlike colonies of coelenterates (Figure 12-2) armed, like jellyfish, with nematocysts. Because colonies of these animals may be inconspicuous (they are often only a few inches high), they may go unnoticed. Except to the occasional person who is hypersensitive to their stings, hydroids generally are more of a nuisance than a hazard. Divers are most likely to be affected on the more sensitive parts of their bodies, such as the inner surfaces of their arms. Although clothing protects most of the body from the stings of hydroids, it will not protect against stings on the hands and face.

Stinging corals (Figure 12-3), often called fire coral, belong to a group of colonial coelenterates known as millepores. They are widespread on tropical reefs among the more familiar stony corals, which they superficially resemble. Contact with the nematocysts of millepores affects humans in about the same way as contact with the nematocysts of stinging hydroids. Common Florida and Bahama species have a characteristic tan-colored blade-type growth, with lighter (almost white) upper portions. *Millepora* may appear in the bladed or encrusting form over rock surfaces or on the branches of soft corals such as alcyonarians. The *Millepora* zone of the outer Florida Keys ranges from 10 to 25 feet deep.

Portuguese Men-o-War (Figure 12-4), which are grouped together in the genus *Physalia,* are colonial hydroids known as siphonophores. Siphonophores differ from the other forms considered here as jellyfish in that each organism is actually a colony of diverse individuals, each performing for the entire colony a specialized function such as swimming or capturing prey. A gelatinous, gas-filled float, which may be 6 inches or more in diameter, buoys the man-o-war at the surface, and from this float trail tentacles as long as 30 feet that bristle with nematocysts. Man-o-war stings can be dangerous to humans, so divers should stay well clear of these animals. Unfortunately, even the most careful diver can become entangled in a man-o-war tentacle, because these nearly transparent structures trail so far below the more visible float. It is

Figure 12-2
Stinging Hydroid

Photo Tony Chess

Figure 12-3
Stinging or Fire Coral

Photo Morgan Wells

Figure 12-4
Portuguese Man-of-War

Photo Morgan Wells

especially difficult to detect fragments of tentacles that have been torn from the colony and are drifting free. The nematocysts on these essentially invisible fragments can be as potent as those on an intact organism, and chances are good that divers who repeatedly enter tropical waters will sooner or later be stung by one.

More properly regarded as jellyfish are a group of coelenterates known as **scyphozoans**, each individual of which is an independent animal. These include the common jellyfishes encountered by divers in all oceans. Although many can sting, relatively few are dangerous. One large jellyfish of the genus *Cyanea* (Figure 12-5) is often encountered by divers in temperate coastal waters of both the Atlantic and Pacific oceans. Divers should be aware that there is a chance of being stung even after they leave the water, because segments of the tentacles of these animals may adhere to the diver's gloves, and touching the glove to bare skin, especially on the face, will produce a sting as painful as any received from the intact animal.

Figure 12-5
Large Jellyfish of Genus *Cyanea*

Photo Tony Chess

The most dangerous of the jellyfish belongs to a tropical subgroup of scyphozoans known as *cubomedusae*, or sea wasps. Sea wasps have an extremely virulent sting; one species in the southwest Pacific has caused death in humans. Fortunately, the more dangerous sea wasps are rarely encountered by divers.

Sea anemones of various species are capable of inflicting painful stings with their nematocysts. These animals frequently look like beautiful flowers, which may deceive people into touching them. The Hell's Fire sea anemone (*Actinodendron*), which is found in the Indo-Pacific region, is an example of such an anemone.

True corals are capable of inflicting serious wounds with their razor-sharp calcarious outer skeletons. Coral cuts are one of the most common hazards facing divers in tropical waters, and contact with corals should be carefully avoided. Divers should be equipped with leather gloves and be fully clothed when working among corals, because coral cuts, if not promptly and properly treated, can lead to serious skin infections.

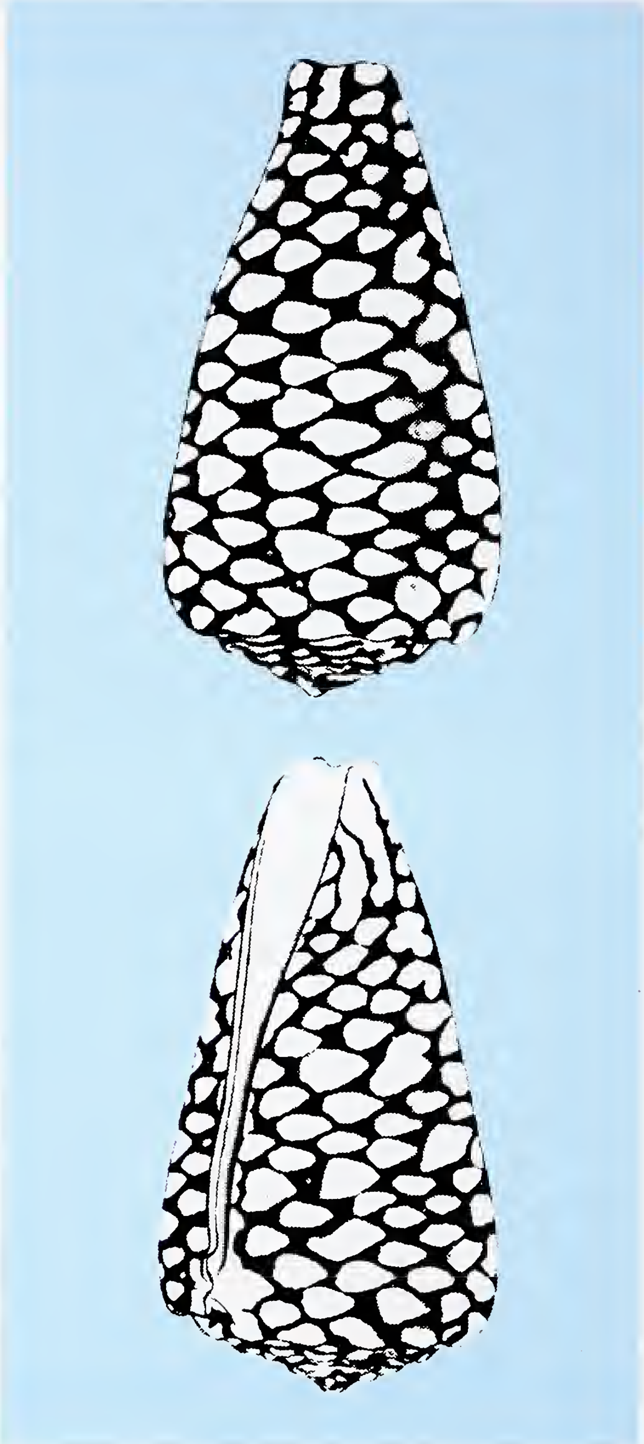
12.2.2 Marine Worms

Marine worms that can be troublesome to divers are classified in a group known as polychaetes. Two types

Figure 12-6
Bristleworm

Photo Richard Rosenthall

Figure 12-7
Cone Shell



Source: NOAA (1979)

reportedly inflict venomous wounds: bristle worms and blood worms.

Bristleworms (Figure 12-6), which divers often encounter when overturning rocks, have tufts of sharp bristles along their segmented bodies that, in many species, can be extended when the animal is irritated. It has not been established that these bristles are venomous, but there is evidence for at least some species that this is so.

Blood worms burrow in mud or sand and some species can be a problem to divers who handle them. Their jaws contain venomous fangs, and their bite is comparable to a bee sting.

12.2.3 Cone Shells

Of the many diverse kinds of shelled mollusks in the sea, only some of the tropical cone shells are hazardous to divers (Figures 12-7 and 12-8). **Cone shells**, characterized by their conical shape, are an especially attractive hazard because collectors are drawn to the colorful shells of the most dangerous species. There are more than 400 kinds of cone shells, each with a highly developed venom apparatus used to stun the small animals that are its prey. The weapon of cone shells is thus an offensive rather than defensive one, a fact that helps to reduce the number of times people handling these shells are stung. Although only a relatively few of the cone shells are dangerous to divers, the stings of some can reportedly be deadly. Because cone shells inject their venom with a harpoonlike structure located at the narrow end of their shells, persons handling these animals should grasp them at the wide end.

Figure 12-8
Anatomy of a Cone Shell

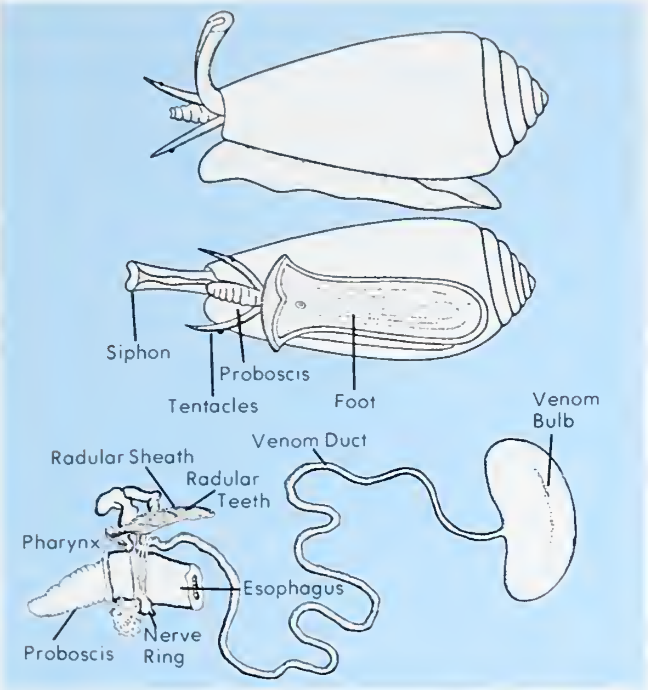


Photo Bruce W. Halstead

Figure 12-9
Rare Australian Blue-Ring Octopus

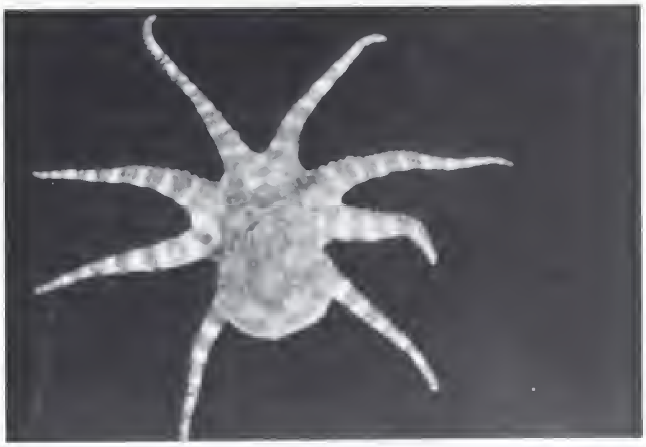


Photo Bruce W. Halstead

12.2.4 Octopuses

Octopuses are timid creatures that will take any opportunity to retreat from divers. Some species, however, can be hazardous to divers who attempt to handle them. When an octopus bites into prey with its parrotlike beak, venom enters the wound and subdues the prey. This venom normally is not toxic to humans, however. Although there have been relatively few cases of octopus bites in humans, one diver in Australia who allowed a rare blue-ring octopus to crawl over his bare skin was bitten on the neck and died within 2 hours. Because the bite of this species can be lethal, the Australian blue-ring octopus (Figure 12-9) should be carefully handled.

12.2.5 Sea Urchins

Among the more troublesome animals for divers working near tropical reefs are venomous **sea urchins**. This is especially true after dark, when visibility is reduced and many of the noxious sea urchins are more exposed than in daylight. Sea urchins may also be a problem in temperate waters, but the species in these regions lack the venom of the tropical species and therefore present a puncture rather than poisoning hazard.

Most difficulties with venomous sea urchins result from accidental contact with certain long-spined species. The smaller secondary spines that lie among the larger primary spines do the most damage; apart from their venom, these spines invariably break off in the wound and, being brittle, frequently cannot be completely removed. Gloves and protective clothing afford some protection against minor brushes with these animals but do not help much when a diver strikes forcefully against them. To avoid painful injury when working close to venomous sea urchins, divers should avoid contact.

Some of the short-spined tropical urchins are reported to be hazardous because they have tiny pincerlike organs, called pedicellariae, that occur among their spines. Although some pedicellariae contain a potent venom, they are very small structures that probably do not threaten divers who incidentally come into contact with the urchins that carry them. When wearing gloves, one can handle these urchins without concern for their pedicellariae.

12.2.6 Fishes

Many fishes inflict venomous wounds. Most do so with their fin spines, but some wound with the spines located on their heads or elsewhere on their bodies. Generally these fishes injure only divers who deliberately handle or provoke them; however, some wound divers who unintentionally touch them or come too close.

Stingrays. Stingrays carry one or more spikelike spines near the base of their flexible tails, which they can use effectively against those who come in contact with them. Although these spines can inflict venomous puncture wounds similar to those of the fishes discussed above, they more often inflict a slashing laceration. Humans are most threatened when they are wading on sandy bottom in shallow water or swimming close to the bottom. Walking with a shuffling motion tends to frighten stingrays away. Stingrays are responsible for more fish stings than any other group of fishes. Species of the family Dasyatidae present the greatest danger, combining as they do large size, the habit of lying immobile on the seafloor covered with sand, and a large spine that is carried relatively far back (compared to those of other stingrays) on a whiplike tail (Figure 12-10). Large rays of this type can drive their spines through the planks of a small boat or through a human arm or leg. Swimmers coming into contact with the bottom have been mortally wounded when struck in the abdomen by a dasyatid stingray lying unseen in the sand.

The urolophid, or round, stingrays have a short muscular caudal appendage to which the sting is attached; they are thus able to deliver severe stings with a whip of their tail. Many of the most common stingray envenomations are caused by round stingrays.

Less dangerous are stingrays of the family Myliobatidae, which includes the bat rays and eagle rays (Figure 12-11), even though these animals can be large and have long venomous spines on their tails. The spines of these species are at the bases of their tails rather than farther back and so are far less effective weapons than the spines of the dasyatid or urolophid rays. The myliobatid rays are also less cryptic than the dasyatids or urolophids: rather than lying immobile on the bottom most of the time, they more often swim through the midwaters, their greatly expanded pectoral fins flapping gracefully like the wings of a large bird. When on the seafloor, myliobatid rays usually root actively in the sand for their shelled prey, and thus are readily seen.

Scorpionfishes. Scorpionfishes are among the most widespread and numerous family of venomous fishes. The family, which numbers several hundred near-shore species, has representatives in all of the world's seas, but the most dangerous forms occur in the tropics. Scorpionfishes usually inject their venom with their dorsal fin spines and less often do so with the spines of their anal and pelvic fins.

Many scorpionfishes are sedentary creatures that lie immobile and unseen on the seafloor. An example is the **sculpin**, a common near-shore scorpionfish species of southern California. Another example, the **stonefish**, is common in the shallow, tropical waters of the western Pacific and Indian Oceans; this species has the most potent sting of all scorpionfishes and has caused deaths among humans. Although stonefish are not aggressive toward divers, their camouflage makes it easy to step on them unless special care is taken.

In contrast to the cryptic sculpin and stonefish, another group of scorpionfishes, the brilliantly hued **lionfishes**

Figure 12-10
Dasyatid Stingray

Photo Morgan Wells

Figure 12-11
Myliobatid Stingray

Photo Edmund Hobson

Figure 12-12
Lionfish

Photo Al Giddings

Figure 12-13
Surgeonfish

Photo Edmund Hobson

(Figure 12-12), stand out strikingly against their surroundings. Because lionfishes are beautiful animals that make little effort to avoid humans, inexperienced divers may be tempted to grasp hold of one. This could prove a painful mistake, because lionfish venom is especially potent.

Other fishes similarly armed with venomous fin-spines include: the **spiny dogfish**, family Squalidae; **weever fishes**, family Trachinidae; **toadfishes**, family Batrachoididae; **stargazers**, family Uranoscopidae; **freshwater** and **marine catfishes**, family Ariidae; **rabbitfishes**, family Siganidae; and **surgeonfishes**, family Acanthuridae. These fishes do not usually generate sufficient force to drive their venom apparatus into their victims; instead, the force is supplied by the victims themselves, who handle or otherwise come into contact with these fishes. A number of fishes, however, do actively thrust their venom apparatus into their victims, an action that often produces a deep laceration; fishes of this type are discussed next.

Surgeonfishes. As noted above, some surgeonfishes (Figure 12-13) can inflict venomous puncture wounds with their fin spines; these wounds are much like those produced by scorpionfishes and other similarly armed fishes. Many surgeonfishes can also inflict deep lacerations with knifelike spines they carry on either side of their bodies, just forward of their tails. Although not conclusive, there is evidence that these spines are venomous in at least some species. The more dangerous surgeonfishes, which belong to the genus *Acanthurus*, usually carry these spines flat against their bodies in integumentary sheaths; however, when threatened, these fish erect these spines at right angles to their bodies and attack their adversaries with quick, lashing movements of their tails. Divers injured by surgeonfishes have usually been hurt while trying to spear or otherwise molest them.

12.2.7 Reptiles

Venomous snakes are a more widespread hazard in fresh water than in the sea. The **cottonmouth water snake**, which has an aquatic bite known to have been fatal to humans, may be the most dangerous animal hazard that divers face in fresh water. This species, which is difficult to identify because of its highly variable coloration, does not show the fear of humans that is characteristic of most aquatic snakes. In regions inhabited by the cottonmouth, divers should avoid any snake that does not retreat from them. The best defense is a noiseless, deliberate retreat. Wet suits afford reasonably good protection but can be penetrated by the teeth of larger specimens. The diver should not attempt to strike back, since this practice may result in multiple bites. Although the evidence is not conclusive, the snake is believed not to dive deeper than about 6 feet. Another species to avoid is the **timber rattlesnake**, an excellent swimmer at the surface. Venomous **sea snakes** occur only in tropical regions of the Pacific and Indian oceans. These reptiles have a highly virulent venom, but fortunately for divers they generally do not bite humans unless roughly handled. Sometimes a sea snake that is caught amid a netload of fishes will bite a fisherman, but generally they are not aggressive toward divers who meet them under water. Sea snakes are especially numerous in the waters near the East Indies. Sea snakes are the most numerous of all reptiles and are sometimes seen in large numbers in the open ocean. Divers most often see them amid rocks and coral, where they prey on small fishes (Figure 12-14). They are agile underwater swimmers, and divers should not lose respect for their deadly bite simply because they are reportedly docile.

Figure 12-14
Sea Snake

Photo John Sneed

12.3 ANIMALS THAT BITE

Serious injuries caused by the bites of non-venomous marine animals are rare. However, the possibility of such injury is psychologically threatening, partly because this hazard has been so widely publicized that many divers are distracted by it. It is important that working divers view this hazard realistically.

12.3.1 Fishes

Sharks have been given more sensational publicity as a threat to divers than any other animal, even though shark bites are among the most infrequent of all injuries that divers sustain in the sea. This notoriety is understandable; injuries from shark bites generally are massive and are sometimes fatal. Nevertheless, only a very few of the many species of sharks in the sea threaten humans.

The vast majority of sharks are inoffensive animals that threaten only small creatures like crabs and shellfish. However, some sharks that are usually inoffensive will bite divers who are molesting them; included here are such common forms as **nurse sharks** (family Orectolobidae) and **swell sharks** (family Scyliorhinidae). These animals appear docile largely because they are so sluggish, but large specimens can seriously injure a diver. Although any large animal with sharp teeth should be left alone, the sharks discussed below may initiate unprovoked attacks on divers.

Most sharks known to attack humans without apparent provocation belong to one of four families: the Carcharhinidae, which include the **gray shark**, **white-tip shark**, **blue shark**, and **tiger shark**; the Carchariidae, which include the **sand shark** (including the species called grey nurse shark in Australia, not to be confused with the animals called nurse sharks in American waters); the Lamnidae, which include the **mako shark** and **great white shark** (Figure 12-15); and the Sphyrnidae, which include the **hammerheads**. All of these are relatively large, active animals whose feeding apparatus and behavior give them the potential to injure divers seriously. Except for the hammerheads, whose name well characterizes their appearance, these sharks all look much alike to the untrained eye. The characteristics distinguishing them would certainly not impress most divers encountering them under water.

Figure 12-15
Great White Shark

Photo Ron and Valerie Taylor

Figure 12-16
Gray Reef Shark

Photo Edmund Hobson

The **great white shark** is reputed to be the most dangerous of all sharks. This shark is credited with more attacks on humans than any other shark species. It attains a length of 20 feet or more.

The **gray reef shark** (Figure 12-16), numerous on tropical Pacific reefs, is typical of these potentially dangerous species. These sharks have repeatedly been incriminated in human attacks. Any creature over about 3 feet long that generally resembles this animal should be regarded cautiously, and if over about 8 feet long, it should be avoided—even if this requires the diver to leave the water. Sharks of these species that range between 3 and 7 feet in length are numerous in shallow tropical waters, and diving operations often cannot be performed unless the presence of sharks in the area is tolerated. When such sharks are in the vicinity, divers should avoid making sudden or erratic movements. Common sense dictates that no injured or distressed animals should be in the water, because these are known to precipitate shark attacks. When operations are conducted in the presence of sharks, each group of divers should include one person who keeps the sharks in view and is alert for changes in their behavior. The chances of trouble are minimal as long as the sharks swim slowly and move naturally. However, the situation becomes dangerous as soon as the sharks assume unnatural postures, such as pointing their pectoral fins downward, arching their backs, and elevating their heads. The moment sharks show such behavior, divers should leave the water. Gray reef sharks are sometimes encountered in large numbers, and when in large groups they may become very aggressive if food is in the water.

Moray eels (Figure 12-17) are a potential hazard on tropical reefs, and a few species occur in the warmer temperate regions of California and Europe. They are secretive animals, with body forms highly specialized for life within reef crevices; they are only rarely exposed on the reef top. Although relatively few grow large enough to threaten divers seriously, some attain a size greater than 5 feet. The moray's powerful jaws, with long needlelike teeth, can grievously wound humans.

Divers injured by morays have usually been bitten when they are reaching into a reef crevice for some object; they were struck by a moray that probably felt threatened or perhaps mistook the diver's hand for prey. The moray will usually release its grip when it recognizes that it has taken hold of something unfamiliar, and if divers can resist the impulse to pull free, they may escape with no more than a series of puncture wounds. But such presence of mind is rare in such a situation, and divers often receive severe lacerations when wrenching their hands from between the backward-pointing teeth of the eel.

Figure 12-17
Moray Eel

Photo Edmund Hobson

Barracudas (Figure 12-18) are potentially dangerous fishes that occur widely in the coastal waters of tropical and subtropical seas. Often exceeding 4 feet in length and with long canine teeth in a large mouth, these fishes have the size and equipment to injure humans severely. Large barracuda often follow divers about, apparently to get a good look at the divers; it is important to remember that even the smallest diver is much larger than anything the barracuda is accustomed to eating. The barracuda's teeth are adapted for seizing the fish that are its prey; however, these teeth are ill-suited to tearing pieces from an animal as large as a human. Attacks on divers are most likely to occur where the barracuda has not had a good look at its victim. Where visibility is limited, for example, the barracuda may see only a moving hand or foot, which may be mistaken for prey. An attack may also occur when a diver jumps into the water, as when entering the sea from a boat. To a nearby barracuda, the diver's splash may simulate the splash of an animal in difficulty—and hence vulnerable—and the barracuda may strike without realizing what made the splash. Thus one should be especially alert in murky water to avoid unnecessary splashing when large barracudas may be present.

Other fishes that bite. Any large fish with sharp teeth or powerful jaws can inflict a damaging bite. Generally, however, such fish are hazardous to divers only when they are handled. The **pufferfishes, wolffishes,** and **triggerfishes** can be especially troublesome in this respect. These fishes have teeth and jaws adapted to feeding on heavily armored prey, and large specimens are quite capable of biting off a human finger.

In the tropics, some of the larger **sea basses** can grow to more than 7 feet. These giant fish, including certain **groupers** and **jewfishes**, are potential hazards. Their mouths can engulf a diver, and there are reports that they have done so.

12.3.2 Reptiles

Reptiles that bite, including turtles, alligators, and crocodiles, are potential hazards to divers, both in freshwater and in the sea.

Turtles are frequently encountered by divers; however, although the larger individuals of some species can injure divers with their bites, these animals are not generally threatening. Although the larger marine turtles have occasionally inflicted minor injuries, several freshwater species are far more vicious and aggressive; these include the alligator snapping turtle and common snapping turtle of American fresh waters. The softshell turtle also may inflict a serious wound.

Figure 12-18
Barracuda

Photo Dick Clarke

Alligators that have been encountered by divers, including the American alligator, have not proved threatening. Nevertheless, the potential for serious injury exists, and divers should be cautious.

Crocodiles are more dangerous than alligators. A species in the tropical western Pacific that enters coastal marine waters is feared far more than sharks by the natives, and with good reason: it is known to have attacked and eaten at least one diver.

12.3.3 Aquatic Mammals

Juvenile and female **seals** and **sea lions** frequently frolic in the water near divers. Underwater encounters with sea lions can be expected if the animals are nearby during a dive. Their activity can be distracting or even frightening, but it is rarely dangerous. Large bull seals and sea lions, although aggressive on the above-water rocks of their breeding rookery, apparently do not constitute a serious threat under water. A potentially greater danger when swimming with seals is being shot by a person hunting illegally. Some divers wear bright markings on their hoods for this reason. If bitten by a seal or sea lion, the diver should consult a physician, because some species may transmit diseases that are infectious among humans.

Common sense dictates that divers avoid large **whales** under water. Usually whales stay clear of divers, so that most incidents occur when divers put themselves in jeopardy by provoking the whales. Whales may be startled when a diver approaches too close and may strike a diver senseless in their sudden surge of evasive action.

Muskrats are potential hazards in fresh water. Usually they attack only if they believe themselves to be threatened; their bites produce only minor wounds. However, there is a serious danger that rabies can be contracted from muskrat bites, so in addition to seeking immediate medical advice, divers who are bitten should make every effort to capture or kill the animal for later examination.

12.4 ANIMALS THAT SHOCK

Among marine animals that produce an electric shock, the only one significantly hazardous to divers is the **electric ray**, which has representatives in all the oceans of the world. The **torpedo ray** of California (Figure 12-19), which can grow to 6 feet in length and weigh up to 200 pounds, is an example. These rays are shaped somewhat like a stingray, except that their "wings" are thick and heavy and their tails are flattened for swimming. Electric rays are slow-moving animals, and alert divers should have little trouble avoiding them. As is true of so many undersea hazards, these animals generally threaten only those divers who molest them. The electric ray's shock, which can be as large as 200 volts, is generated by modified muscles in the forward part of the animal's disc-shaped body. The shock, which is enough to electrocute a large fish, can jolt a diver severely.

12.5 ANIMALS POISONOUS TO EAT

Most seafoods are edible and nourishing; however, several of the most toxic substances known are sometimes found in marine organisms. Mollusk shellfish, such as clams, mussels, and oysters, are sometimes poisonous to eat. These shellfish become poisonous because they feed on toxic dinoflagellates, which are

Figure 12-19
Torpedo Ray

Photo Tony Chess

microscopic plankton. Most of these episodes of poisoning have occurred along the Pacific coast from California to Alaska; the northeast coast from Massachusetts to Nova Scotia, New Brunswick and Quebec; and in the North Sea countries of Britain and West Germany. It is advisable to check with local authorities to determine what periods are safe for eating mollusk shellfish. Violent intoxications and fatalities have also been reported from eating tropical reef crabs; these should not be eaten without first checking with the local inhabitants. Numerous species of tropical reef fishes are known to be poisonous to eat because they cause a disease known as ciguatera (see Section 18 for a discussion of ciguatera poisoning treatment). An edible fish in one locality may be deadly in another.

Figure 12-20
Examples of Pufferfish

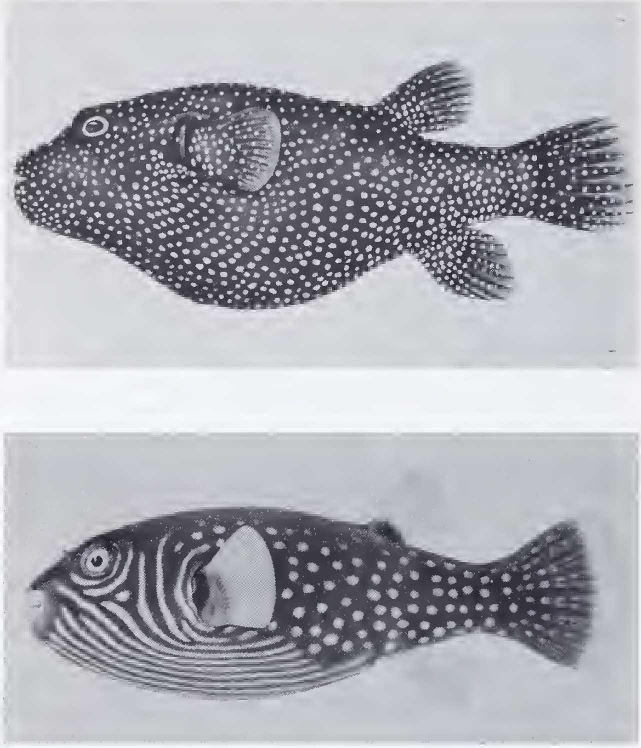


Photo Bruce W. Halstead

In addition, most pufferfish (Figure 12-20) contain a deadly poison known as tetrodotoxin, and puffers and related species should be carefully avoided.

SECTION 13
WOMEN AND DIVING

WOMEN AND DIVING

13

13.0 GENERAL

Women have played significant roles as divers for many years, beginning with their work as Hae-Nyu and Ama divers in Korea and Japan. The number of certified female sport divers, instructors, research, and commercial divers in America has increased significantly since the early 1970's, and national certification agencies report that approximately 25 percent of newly certified divers are women. This increase in the female diving population has raised many issues not formerly addressed. Some of these questions are asked by women divers themselves, and others are raised by researchers in hyperbaric medicine and physiology. This section discusses several of these topics.

13.1 PHYSIOLOGICAL CONSIDERATIONS

Women have proven themselves to be safe and competent divers. They are capable of participating in the same training and withstanding most of the same stresses as their male colleagues. However, the anatomical and physiological differences between men and women have some implications for women divers.

13.1.1 Anatomical Differences

Some of the anatomical differences between women and men are obvious, but others are more subtle. Even an athletic woman in good physical condition has less muscle mass than a man in comparable condition, because the male hormone, testosterone, which is needed for the development of large muscles, is present only in reduced quantities in women. However, all divers benefit from being in good physical condition, and female divers can improve their strength and aerobic capabilities with specially designed exercise programs.

Women generally have a lower center of gravity than men, and have relatively longer trunks and shorter legs, which means that most of a woman's weight is distributed at a lower point than a man's. Moreover, the shape of several joints, such as those at the hip and elbow, differ in women, because the bones at these joints meet at slightly different angles than is the case for men. In addition, a greater percentage of total body weight is composed of fatty tissue in women than men.

Another anatomical difference between men and women occurs in the cardiovascular and respiratory systems (heart, lungs, and circulation). Even when relative weight is taken into consideration, a woman's heart and lungs are smaller than a man's. Women tend to breathe more shallowly, although their breathing is equally efficient. Consequently, in comparison to male divers, a female diver takes less air into her lungs and her heart rate is slightly higher. These facts have implications for diving. For example, a female diver may use less air than her male buddy for the same dive. Women also have increased pulse and respiration rates and may tend to work closer to their maximum exertion level when diving. It is important for all divers to pace themselves carefully under water and to avoid maximum or near-maximum exertion as much as possible.

13.1.2 Diving During the Menstrual Period

One of the most common questions asked by female divers is, "Should I dive during my period?" Before answering that question, it is important to understand certain hormonal changes that occur in a woman's body in the course of her normal 20-45 day cycle. Several hormones are involved in this cycle: hypothalamic and pituitary hormones, which are secreted by glands in the brain, adrenal hormones, and the two ovarian hormones, estrogen and progesterone. A woman's estrogen level increases up to ovulation and then drops slightly, while the level of progesterone increases rapidly after ovulation and then decreases during menstruation. The female sexual cycle is thus regulated by various hormones. The levels of hormones are highest before menstruation and lowest during menstruation. The drop in estrogen and progesterone levels triggers menstruation.

Based on current knowledge, there is no reason for women to refrain from diving during their periods if they feel well. As in all diving, however, it is important not to dive to the point of fatigue. Fluid retention, which can occur during the premenstrual period, may be a problem for some women divers. Although the effect of fluid retention on the susceptibility of divers to decompression sickness has not yet been established, women divers should use common sense and plan their dives so that they are well within the no-decompression limits during the premenstrual and menstrual portions of their cycles.

Some women have asked whether there is a greater likelihood of shark attack during their periods. According to some recent Australian research, there is no evidence that sharks are attracted to menstruating women (Edmonds, Lowry, and Pennefather 1981). Sharks thus may not pose a greater threat to women divers during menstruation than at any other time.

13.1.3 Birth Control Methods

Women divers should select a method of birth control on the basis of their physician's advice and their own preference. The physician should be informed that the patient is a diver, which may be an important consideration if either an intrauterine device or birth control pills are selected. In general, however, women who have no adverse responses to the method of birth control they are using on land should have no difficulty with the same method when diving.

13.1.4 Temperature Regulation

Staying thermally comfortable during a dive is important both for enjoyment and to accomplish the work planned for a dive. Despite the fact that women have a layer of subcutaneous fat that is a good insulator, many women become chilled quickly when they dive.

By studying the responses of women in cool water, two factors involved in the sensitivity to cold have emerged: percentage of body fat and ratio of surface area to body mass (Kollias et al. 1974). Lean women with 27 percent or less body fat have a larger ratio of surface area to body mass than fatter women; women with such a low percentage of body fat chill more rapidly than women or men with a higher body fat percentage. Both men and women who have 30 percent or more body fat will experience the same amount of heat loss in water.

Suitable exposure suits, properly fitted, are recommended to ensure thermal protection (see Section 5.4). Although wearing an exposure suit on the surface on a warm day will make any diver hot, the problem may be exacerbated in women because they have fewer sweat glands than men and do not begin to sweat until their body temperature is 2-3°F higher than the temperature that causes sweating in men (Kollias et al. 1974). (See Sections 3.4 and 3.5 for a more detailed discussion of thermal regulation.)

13.1.5 Aging and Diving

Many middle-aged divers, both male and female, continue to enjoy the sport of scuba diving. In fact, many middle-aged and older men and women learn to dive for the first time at this stage of life. Although advancing age may lessen people's interest in competitive or strenuous sports, scuba diving can be a lifelong recreational activity. Older divers should have an annual diving physical examination, and they should swim several times a month with mask, fins, and snorkel to stay in good diving condition. In addition, older divers should watch their weight, avoid fatigue, ascend and descend at a reasonable rate, and consider the potential interactions between pressure and any prescribed medication before diving.

Usually between the ages of 45 and 50, women undergo a series of hormonal changes called menopause. Ovulation fails to occur during the monthly cycle and estrogen production by the ovaries decreases. Abrupt changes in hormonal levels of estrogen and progesterone may cause a variety of symptoms, including hot flashes, irritability, fatigue, and anxiety. A woman suffering from any of these symptoms should not dive if these symptoms are sufficiently acute to make her feel uncomfortable.

Older divers, both male and female, may be more susceptible to decompression sickness. Therefore, middle-aged and older divers should use conservative judgment in dive planning and should remain at a particular depth for less time than the maximum no-decompression tables permit.

13.2 WOMEN DIVERS AND DECOMPRESSION SICKNESS

Many factors are believed to increase an individual's susceptibility to decompression sickness, including age, degree of body fat, and general vascular condition. Because the U.S. Navy dive tables were developed for young, physically fit males, their applicability to other groups of divers, especially to women, has been questioned. Women usually have a relatively greater amount of subcutaneous fat than men. They also experience hormonal changes during their menstrual cycles that can cause fluid retention, and some women use birth control pills that may affect their circulation. All of these factors suggest that the risk of decompression sickness may be higher for women than for men.

In one study, a 3.3-fold increase in the incidence of decompression sickness was reported among women divers, as compared with divers in the male control group (Bangasser 1978). In this study, other distinguishing factors, such as age and weight/height factors, were not significantly different for the female and male groups. These results are too tentative to use as the basis for any conclusion concerning the relative bends susceptibility between males and females. However, women divers should be conservative in their use of the Navy tables and should make 3- to 5-minute safety stops at 10 feet (3 meters) after deeper dives.

13.3 DIVING DURING PREGNANCY

As more women enter sport and professional diving, the chance that dives will inadvertently take place during pregnancy increases. Women who would not knowingly dive during pregnancy may dive unwittingly during the first few weeks of pregnancy, before they discover that they are pregnant. Several factors that could affect both the mother and the fetus indicate that women should take care to avoid diving when there is any chance that they are pregnant.

13.3.1 Effects of Diving on the Fetus

The health and safety of the developing fetus are of primary importance to expectant mothers. Since scuba divers are exposed to increased hydrostatic pressure and to increased partial pressures of oxygen and nitrogen, the effects of these pressures on the fetus have been investigated.

13.3.1.1 Direct Pressure

Since the fetus is completely enclosed in amniotic fluid and no air spaces are present, there is no direct effect of increased pressure on the fetus. During a dive, a fetus will not experience squeeze, e.g., pressure on the ear drums.

13.3.1.2 Effects of Changes in Oxygen Pressure

Oxygen is essential to maintaining life, and either a lack or an excess of oxygen can have harmful effects. To some extent, the fetus is protected from either extreme, but circumstances affecting the mother's oxygenation must be considered in terms of their potential effects on the fetus. As long as the diver has an adequate compressed-air supply, too little oxygen (hypoxia) is unlikely. (Hypoxia is thus a potentially greater problem in breath-hold than in scuba diving.)

At any depth below sea level, the oxygen pressure, even when air is the breathing medium, is higher than it is at sea level. For example, breathing compressed air at 132 fsw (40.2 msw) produces an inspired oxygen pressure of 4 ATA. However, a fetus is most likely to be exposed to too much oxygen (hyperoxia) if the mother breathes pure oxygen under pressure, as might occur during hyperbaric treatment for decompression sickness or gas embolism. To date, even under such circumstances, fetal effects have not been reported; however, experience is not sufficiently extensive to be conclusive.

13.3.1.3 Effects of Increased Nitrogen Pressure

As a diver descends, the body absorbs increasing amounts of nitrogen. If the nitrogen is eliminated too quickly (which could happen during a rapid ascent), decompression sickness may occur, either during ascent, at the surface, or after surfacing. Decompression sickness occurs when the nitrogen in solution in a diver's tissues comes out of solution in the form of bubbles (see Section 3.2.3.2).

Any bubbles that form in the fetus could obstruct blood flow and cause major developmental anomalies or death. Research has been conducted on bubble formation in the fetus using laboratory studies of animals or retrospective surveys of women divers (Lanphier 1983, Bolton 1980, Bangasser 1978). The questions addressed were: Does diving cause birth defects? Are bubbles more or less likely to form in the fetus than in the mother? If the mother develops decompression sickness, what happens to the fetus?

Scuba diving and birth defects. The results of one survey (Bolton 1980) showed a birth defect rate of 5.5 percent among women who had dived to depths of 100 fsw (30 msw) or greater during pregnancy; this incidence is statistically greater than the rate observed in infants born to a control group of non-diving women. Although this finding was significant, the rate of birth defects among all U.S. women (approximately 3-3.5 percent) is not much lower than that found in the divers. Results from another survey of women who had dived during pregnancy failed to demonstrate a relationship between diving while pregnant and birth defects (Bangasser 1978).

Data gathered from animal studies thus far show no conclusive evidence of a connection between increased pressure and fetal abnormalities. For example, rats exposed to high pressures during peak embryonic development had no increase in birth defects (Bolton and Alamo 1981). In a similar experiment, pregnant sheep were exposed to a pressure of 4.6 atmospheres early in pregnancy, that is, during peak embryonic development (Bolton-Klug et al. 1983). Toward the end of pregnancy, the fetuses were examined anatomically and were found to have no detectable abnormalities.

Bubble formation in the fetus during a dive. Research on the likelihood of bubble formation in the fetus of a pregnant woman during a dive has resulted in controversial findings (Bangasser 1979). Early experiments on dogs and rats showed a resistance to bubble formation in the fetus. More recent experiments using sheep and goats as experimental models have produced somewhat conflicting results. When sheep were put under a pressure of 165 fsw (50 msw) for 20 minutes, a Doppler bubble monitor detected bubbles in the mothers but not in the fetuses. The lambs developed normally after birth (Nemiroff et al. 1981). In another hyperbaric experiment, bubbles were detected both in the dams and fetuses of sheep and goats; however, these lambs and kids were also normal on delivery (Powell and Smith 1985).

These experiments show that, although the fetus is probably less susceptible to bubble formation during decompression than the mother, there is a real potential danger of fetal bubble formation during decompression.

Effect of maternal decompression sickness on the fetus. Although evidence pointing to the potentially adverse consequences of maternal decompression sickness on the developing fetus is not definitive, it reinforces the view that pregnant women should not dive. Although early studies on dogs and rats (McIver 1968, Chen 1974) indicated that the fetus would suffer no harm even if the mother had decompression sickness, more recent studies (Nemiroff et al. 1981, Lehner et al. 1982) on sheep report different results. If sheep dived late in gestation and did not incur decompression sickness, the lambs were born healthy (Nemiroff et al. 1981); however, if pregnant sheep developed decompression sickness immediately before delivery, their lambs were stillborn (Lehner et al. 1982). Decompression sickness in a pregnant woman thus might also be associated with fetal morbidity and mortality.

13.3.1.4 Pregnancy and Diving

Although obstetricians encourage patients to continue their favorite sports during pregnancy as long as they are comfortable and use common sense, hyperbaric pnysicians take the most conservative position and recommend that their patients discontinue diving while they are pregnant, since so much is still unknown about the effects of diving on the fetus. Considering the evidence to date, the conflicting results of animal as well as human studies, and the seriousness of the potential consequences, *NOAA recommends that women in the agency not dive during pregnancy.* Women divers who personally elect to continue diving during pregnancy despite this recommendation should do so only on the advice of a trained hyperbaric physician.

WARNING

Women Should Not Dive While Pregnant

13.4 TRAINING CONSIDERATIONS

Scuba instructors have observed several tendencies common among women divers. For example, many women prefer to learn new skills in small steps rather than to master complex tasks in one step. Women also tend to over-learn a skill before having confidence in their mastery, and they may also be more conservative than men when planning their dives (S. Bangasser, personal communication). Because some women have not had much experience in handling mechanical equipment, they may need additional training to learn how to assemble and maintain their equipment.

Psychological studies of experienced male and female divers have not demonstrated any important basic differences in the psychology of men and women divers (Lanphier, personal communication). It is important that women divers, like men divers, develop the independent competence and confidence they need to dive safely and to assist other divers in an emergency.

13.5 EQUIPMENT FOR THE SMALLER DIVER

In the past few years, the diving industry has made great advances in manufacturing equipment to fit the smaller diver. (This development has also helped small men and younger divers of both sexes.) Properly sized diving equipment is now readily available.

Smaller divers should pay extra attention to equipment selection and fit. Masks should seal completely, leave the hair free, and be comfortable. A snorkel with a smaller mouthpiece is recommended for anyone with a narrow mouth. If need be, the mouthpiece on a standard regulator can be replaced with a more comfortable model. Buoyancy devices are available in many lengths and chest sizes and should be selected for size, comfort, and their ability to float the diver in a safe position on the surface (see Section 5.3.2). Tanks that are smaller and lighter in weight are also available. Hoods, boots, and gloves are made in smaller sizes and are available at many dive shops. Figure 13-1 shows a scientist on an underwater mission wearing properly fitted clothing and equipment.

WARNING

Equipment Fit and Comfort Are Essential to Dive Safety

Figure 13-1
Scientist on Research Mission

Photo Ronald Bangasser

Selecting a proper fitting wet suit takes more time and effort than locating other types of properly fitted equipment. Although suits are manufactured for women, many women cannot be properly fitted in a standard off-the-shelf suit. A diver renting a wet suit may need to wear a top of one size and a bottom of a different size. Since splitting sizes can be a problem for the owner of the dive shop, active female divers should invest in a custom wet suit. Zippers make donning and doffing easier and provide a snug fit. With properly fitted gear, small divers—whether male or female—can enjoy the dive, concentrate on the task at hand—not the gear—and feel comfortable and confident about diving.

SECTION 14
AIR DIVING AND DECOMPRESSION

AIR DIVING AND DECOMPRESSION

14

14.0 GENERAL

Diving with air as the breathing medium may be conducted using a variety of life-support equipment. The most frequently used mode is open-circuit scuba, where the diver carries the compressed air supply, but divers can also use umbilical-supplied air with a scuba regulator, a full-face mask, a lightweight diving helmet, or deep-sea diving equipment. This section deals with planning for air dives, methods of calculating air supply requirements, and the decompression aspects of air diving.

14.1 DIVE PLANNING

Careful and thorough planning are the keys to conducting an efficient diving operation and are also imperative for diver safety. The nature of each dive operation determines the scope of the planning required. The dive plan should be devised to take into account the ability of the least qualified diver on the team and be flexible enough to allow for delays and unforeseen problems. It should include at least the following items.

Definition of Objectives:
- A clear statement of the purpose and goals of the operation.

Analysis of Pertinent Data:
- Surface conditions, such as sea state, air temperature, and wind chill factor;
- Underwater conditions, including water temperature, depth, type of bottom, tides and currents, visibility, extent of pollution, and hazards; and
- Assistance and emergency information, including location, status, and contact procedures for the nearest decompression chamber, air evacuation team, Coast Guard, and hospital.

Schedule of Operational Tasks for All Phases:
- Transit to the site;
- Assembling dive gear and support equipment;
- Predive briefing;
- Calculating allowable/required bottom time;
- Recovery;
- Cleaning, inspection, repair, and storage of gear; and
- Debriefing of divers and support personnel.

Diving Mode Selection:
- Open-circuit scuba;
- Surface-supplied;
- Mixed gas; or
- Saturation.

Equipment and Supplies Selection:
- Breathing gas, including a backup supply;
- Dive platform and support equipment, including diver/crew shelter;
- Oxygen resuscitator;
- Dive flag; and
- Diving gear, tools, etc.

Diving Team Selection:
- Dive master;
- Medical personnel;
- Tenders/timekeeper; and
- Coxswain/surface-support personnel.

Briefing/Debriefing the Diving Team:
- The objective and scope of the operation;
- Conditions in the operating area;
- Diving techniques and equipment to be used;
- Personnel assignments;
- Particular assignments for each diver;
- Anticipated hazards;
- Normal safety precautions;
- Any special considerations; and
- Group discussion period to answer questions from members of the diving team.

Final Preparations and Safety Checks:
- Review of dive plan, its impact on the operation, and all safety precautions;
- Outline diving assignments and explain their sequence;
- Complete and post on-site emergency checklist;
- Review diver qualifications and conditions; and
- Secure permission from command or boat captain for dive.

14.1.1 Selection of Diving Equipment

The selection of the proper diving equipment depends on environmental conditions, qualifications of diving personnel, objectives of the operation, and diving procedures to be used. Although most diving is performed at depths less than 130 fsw (39.3 msw) and often uses open-circuit scuba, some missions can be accomplished using only skin diving equipment. Other more complex assignments require surface-supplied or closed-circuit breathing equipment. Depth and duration of the dive, type of work to be accomplished (heavy work, light work, silent work), temperature of the water, velocity and nature of current, visibility, logistics, and the diver's experience and capabilities all influence the selection of diving equipment. Detailed descriptions of the various types of diving equipment are presented in Section 5. For planning purposes, the following guidelines may be used in selecting diving equipment.

Breath-Hold Diving Equipment

Generally Used For:
- Scientific observation and specimen collection in shallow water in areas where more complex equipment is a disadvantage or is not available
- Shallow-water photography
- Scouting for diving sites

Major Advantages:
- Less physical work required to cover large surface areas
- Simplified logistics
- Fewer medical complications

Major Disadvantages:
- Extremely limited in depth and duration
- Requires diver to develop breath-holding techniques
- Can only be used in good sea conditions

Open-Circuit Scuba

Generally Used For:
- Scientific observation
- Light underwater work and recovery
- Sample collection
- Shallow-water research
- Ship inspection and light repair

Major Advantages:
- Minimum support requirements
- Mobility
- Accessibility and economy of equipment and breathing medium
- Portability
- Reliability

Major Disadvantages:
- Lack of efficient voice communication
- Limited depth and duration

Umbilical-Supplied Systems

Generally Used For:
- Scientific investigation
- Ship repair and inspection
- Salvage
- Long-duration scientific observation and data gathering
- Harsh environments (low visibility, strong currents, polluted water)

Major Advantages:
- Ease of supplying heat
- Long duration
- Voice communication
- Protection of diver from environment

Major Disadvantages:
- Limited mobility
- Significant support requirements

Closed-Circuit Scuba

Generally Used For:
- Observations of long duration

Major Advantages:
- Mixed-gas capability
- No noise or bubbles
- Conservation of breathing medium
- Long duration

Major Disadvantages:
- Complicated maintenance
- Extensive training requirements
- Lack of efficient voice communication.

14.1.2 Dive Team Organization

14.1.2.1 Dive Master

Dive masters have complete responsibility for the safe and efficient conduct of diving operations. They must be experienced divers who are qualified to handle the requirements of the proposed dive. When no dive master is present, diving should not be conducted. The dive master's responsibilities are many, and include but are not necessarily limited to:

- Overall responsibility for the diving operation
- Safe execution of all diving
- Preparation of a basic plan of operation, including evacuation and accident plans
- Liaison with other organizations
- Selection of equipment
- Proper maintenance, repair, and stowage of equipment
- Selection, evaluation, and briefing of divers and other personnel
- Monitoring progress of the operation and updating requirements as necessary
- Maintaining the diving log
- Monitoring of decompression (when required)
- Coordination of boat operations when divers are in the water.

The dive master is responsible for assigning all divers to an operation and for ensuring that their qualifications are adequate for the requirements of the dive. The dive master must ensure that all divers are briefed thoroughly about the mission and goals of the operation. Individual responsibilities are assigned to each diver by the dive master. Where special tools or techniques are to be used, the dive master must ensure that each diver is familiar with their application.

Enough training and proficiency dives should be made to ensure safe and efficient operations. During especially complex operations or those involving a large number of divers, dive masters should perform no actual diving but should instead devote their efforts entirely to directing the operation.

The dive master is in charge when divers are in the water during liveboating operations. Before any change is made to the boat's propulsion system (e.g., change in speed, direction, etc.), the boat captain must clear the change with the dive master.

14.1.2.2 Diving Medical Officer/Diving Medical Technician

When it not practical to have a qualified diving medical officer on site, a Diving Medical Technician trained in the care of diving casualties may be assigned. An individual so trained is able both to respond to emergency medical situations and to communicate effectively with a physician located at a distance from the diving site. There are specialized courses available to train Diving Medical Technicians in the care of diving casualties (see Section 7.3).

In the event that neither a physician nor a trained technician is available, the dive master should obtain the names and phone numbers of at least three diving medical specialists who can be reached for advice in an emergency. Emergency consultation is available from the service centers listed below. Referred to as a "Bends Watch," each of these services is available to provide advice on the treatment of diving casualties:

- Navy Experimental Diving Unit, Panama City, FL 32407, telephone (904) 234-4351, 4353;
- National Naval Medical Center, Naval Medical Research Institute, Bethesda, MD 20814, telephone (202) 295-1839;
- Brooks Air Force Base, San Antonio, TX 78235, telephone (512) 536-3278 (between 7:30 a.m. and 4:15 p.m. CST, emergency calls are also received on (512) 536-3281); and
- Diver's Alert Network, Duke University Medical Center, Durham, NC 27710, telephone (919) 684-8111 (ask for the Diving Accident Physician).

Diving personnel should obtain and keep the phone numbers of these facilities, especially if they will be diving in remote areas.

14.1.2.3 Science Coordinator

On missions where diving is performed in support of scientific programs, a science coordinator may be needed. The science coordinator is the prime point of contact for all scientific aspects of the program, including scientific equipment, its use, calibration, and maintenance. Working with the dive master, the science coordinator briefs divers on upcoming missions and supervises the debriefing and sample or data accumulation after a dive.

14.1.2.4 Divers

Although the dive master is responsible for the overall diving operation, each diver is responsible for being in proper physical condition, for checking out personal equipment before the dive, and for thoroughly understanding the purpose and the procedures to be used for the dive. Divers also are responsible for using safe diving procedures and for knowing all emergency procedures.

14.1.2.5 Tender for Surface-Supplied Diving

The tender must be qualified to tend divers independently and to operate all surface-support equipment. To use manpower efficiently, the tender may be a qualified diver used in a diver-tender rotation system. Although there is no specific requirement that tenders be qualified divers, they should be trained in theory and operational procedures by the divers and diving supervisors (see Section 7.2). Ideally, tenders should be trained by instructors and be assigned to diving operations by the diving supervisors. A tender-assistant may assume the tender's responsibilities when the assistant is working under the direct supervision of fully qualified diving and tending personnel. Another tender, diver, or qualified person should be assigned as communications person, console operator, timekeeper, recordkeeper, and diver's assistant.

It is recommended that one qualified person be designated as standby diver, ready to enter the water promptly in an emergency. The standby diver may accept tender responsibilities in routine operations; in more complex diving operations, however, the standby diver must be free of all other duties. A tender must be available and ready to tend the standby diver during an emergency.

14.1.2.6 Support Divers and Other Support Personnel

In most diving operations, the number and types of support divers depend on the size of the operation and the type of diving equipment used. As a general rule, those surface-support personnel working directly with the diver also should be qualified divers. Using unqualified personnel who do not understand diving techniques and terminology may cause confusion and be dangerous. Persons not qualified as divers can be used when the need arises only after they have demonstrated to the satisfaction of the dive master that they understand procedures adequately.

14.1.3 Environmental Conditions

Environmental conditions at a dive site should be considered when planning a diving operation. Environmental conditions can be divided into surface environmental conditions and underwater environmental conditions. Surface conditions include weather, sea state, and amount of ship traffic. Underwater conditions include depth, bottom type, currents, water temperatures, and visibility. Regional and special diving conditions are discussed in Section 10.

14.1.3.1 Surface Environmental Conditions

Weather conditions are an important factor to consider when planning a dive. Whenever possible, diving operations should be cancelled or delayed during bad weather. Current and historical weather data should be reviewed to determine if conditions are acceptable or are predicted to continue for a sufficient amount of time to complete the mission. Personnel should avail themselves of the continuous marine weather broadcasts provided by NOAA on the following frequencies: 162.40 MHz, 162.475 MHz, or 162.55 MHz, depending on the local area. These broadcasts can be heard in most areas of the United States and require only the purchase of a VHF radio receiver. Weather radios are designed to pick up NOAA radio broadcasts only. A boater with such a set will hear regular weather forecasts and special marine warnings any time of the day or night. Although all three receivers pick up weather signals from approximately the same distance, the two-way systems have the advantage of transmission capability.

NOTE

The flag system for weather warnings is no longer in general use; all weather reports are now transmitted by radio.

In some cases, surface weather conditions may influence the selection of diving equipment. For instance, even though water temperature may permit the use of standard wet suits, cold air temperature and wind may dictate that a variable-volume dry suit (or equivalent) be worn when diving from an open or unheated platform.

Whenever possible, avoid or limit diving in moderate seas (see Table 14-1). Sea state limitations depend to a large degree on the type and size of the diving platform. Diving operations may be conducted in rougher seas from properly moored larger platforms such as diving barges, ocean-going ships, or fixed structures. Divers using self-contained equipment should avoid entering the ocean in heavy seas or surf, as well as high, short-period swell. If bad weather sets in after a diving operation has commenced, appropriate recall signals should be employed. Except in an emergency, divers should not attempt scuba or surface-supplied diving in rough seas (see Figure 14-1).

Because many diving operations are conducted in harbors, rivers, or major shipping channels, the presence of ship traffic often presents serious problems. At times, it may be necessary to close off the area around the dive site or to limit the movement of ships in the dive site's vicinity. Ship traffic should be taken into consideration during dive planning, and a local "Notice to Mariners" should be issued. Any time that diving operations are to be conducted in the vicinity of other ships, these other vessels should be notified by message or signal that diving is taking place. Signal flags, shapes, and lights are shown in Table 14-2.

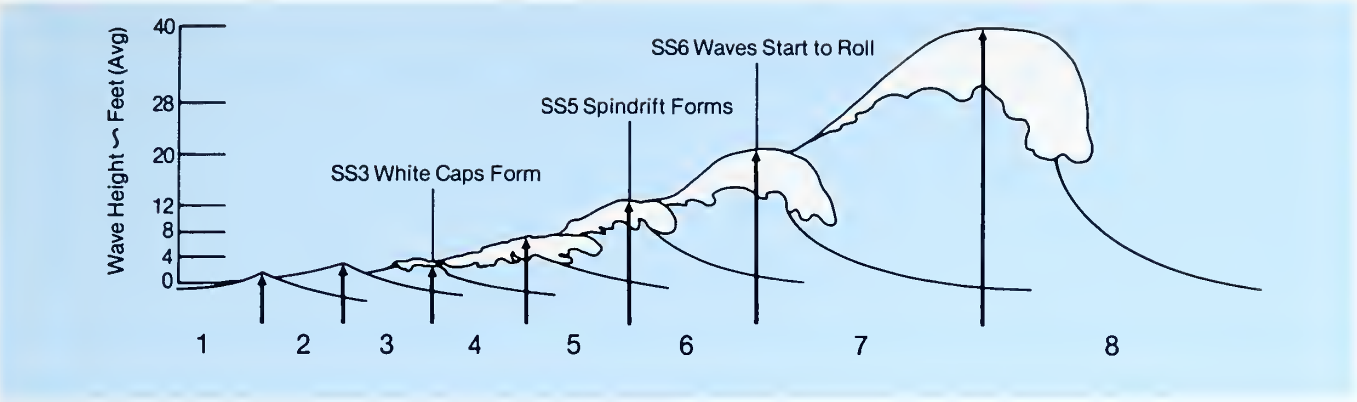
If the dive operation is to be carried on in the middle of an active fishing ground, it is necessary to anticipate that people with various levels of experience and competence will be operating small boats in the vicinity. The diving team should assume that these operators are not acquainted with the meaning of diving signals and should take the necessary precautions to ensure that they remain clear of the area.

The degree of surface visibility is important. Reduced visibility may seriously hinder or force postponement of diving operations. If operations are to be conducted in a known fog-belt, the diving schedule should allow for probable delays caused by low visibility. The safety of the diver and support crew is the prime consideration in determining whether surface visibility is adequate. For example, in low surface visibility conditions, a surfacing scuba diver might not be able to find the support craft or might be in danger of being run down by surface traffic.

14.1.3.2 Underwater Environmental Conditions

Dive depth is a basic consideration in the selection of personnel, equipment, and techniques. Depth should be determined as accurately as possible in the planning

Figure 14-1
Sea States



Source: Bunker Ramo Corp.

phases, and dive duration, air requirements, and decompression schedules (when required) should be planned accordingly.

Type of bottom affects a diver's ability to see and work. Mud (silt and clay) bottoms generally are the most limiting because the slightest movement will stir sediment into suspension, restricting visibility. Divers must orient themselves so that any current will carry the suspended sediment away from the work area, and they also should develop a mental picture of their surroundings so that an ascent to the surface is possible even in conditions of zero visibility.

Sand bottoms usually present little problem for divers because visibility restrictions caused by suspended sediment are less severe than is the case for mud bottoms. In addition, sandy bottoms provide firm footing.

Coral reefs are solid but contain many sharp protrusions. Divers should wear gloves and coveralls or a wet suit for protection if the mission requires contact with the coral. Divers should learn to identify and avoid corals and other marine organisms that might inflict injury (see Section 12).

Currents must be taken into account when planning and executing a dive, particularly when using scuba. When a boat is anchored in a current, a buoyed safety line at least 100 feet (30.3 m) in length should be trailed over the stern during diving operations. If, on entering the water, a diver is swept away from the boat by the current, he or she can use this safety line to keep from being carried down current.

Free-swimming descents should be avoided in currents unless provisions have been made to reach safety. Descent from an anchored or fixed platform into water with currents should be made along a weighted line. A line also should be used unless adequate provisions are made for a pickup boat to operate down current so that surfacing some distance from the entry point will not be dangerous. A knowledge of changing tidal currents may allow divers to drift down current and to return to the starting point on the return current.

Tidal changes often alter the direction of current and sometimes carry sediment-laden water and cause low visibility within a matter of minutes. Tidal currents may prevent diving at some locations except during slack tides. Because a slack tide may be followed by strong currents, divers should know the tides in the diving area and their effects.

Currents generally decrease in velocity with depth, and it may therefore be easier to swim close to the bottom when there are swift surface currents. However, current direction may change with depth. When there are bottom currents, it is useful to swim into the current rather than with the current; this facilitates return to the entry point at the end of the dive. Divers should stay close to the bottom and use rocks (if present) to pull themselves along.

Water temperature is a major factor to consider in planning a diving operation because it has a significant effect on the type of equipment selected and, in some cases, determines the practical duration of the dive. A thermocline is a boundary layer between waters of different temperatures. Although thermoclines do not pose a direct hazard to divers, their presence may affect the selection of diving dress, dive duration, or equipment. Thermoclines occur at various water levels, including levels close to the surface and in deep water. Temperature may vary from layer to layer. As much as a 20°F (a range of 11°C) variation has been recorded between the mixed layer (epilimnion) above the thermocline and the deeper waters (hypolimnion) beneath it.

Underwater visibility depends on time of day, locality, water conditions, season, bottom type, weather, and currents. Divers frequently are required to dive in water where visibility is minimal and sometimes at the zero level. Special precautions are appropriate in either of

Table 14-1
Sea State Chart

Sea-General		Wind				Sea						
						Wave Height Feet						
Sea State	Description	(Beaufort) Wind Force	Description	Range (Knots)	Wind Velocity (Knots)	Average	Average $\frac{1}{10}$ Highest	Significant Range of Periods (Seconds)	T (Average Period)	I (Average Wave Length)	Minimum Fetch (Nautical Miles)	Minimum Duration (Hours)
0	Sea like a mirror.	U	Calm	Less than 1	0	0	0	—	—	—	—	—
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1-3	2	0.05	0.10	up to 1.2 sec.	0.5	10 in.	5	18 min.
1	Small wavelets, still short but more pronounced; crests have a glassy appearance, but do not break.	2	Light Breeze	4-6	5	0.18	0.37	0.4-2.8	1.4	6.7 ft.	8	39 min.
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7-10	8.5 10	0.6 0.88	1.2 1.8	0.8-5.0 1.0-6.0	2.4 2.9	20 27	9.8 10	1.7 2.4
2 3	Small waves, becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	12 13.5 14 16	1.4 1.8 2.0 2.9	2.8 3.7 4.2 5.8	1.0-7.0 1.4-7.6 1.5-7.8 2.0-8.8	3.4 3.9 4.0 4.6	40 52 59 71	18 24 28 40	3.8 4.8 5.2 6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray).	5	Fresh Breeze	17-21	18 19 20	3.8 4.3 5.0	7.8 8.7 10	2.5-10.0 2.8-10.6 3.0-11.1	5.1 5.4 5.7	90 99 111	55 65 75	8.3 9.2 10
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22-27	22 24 24.5 26	6.4 7.9 8.2 9.6	.13 16 17 20	3.4-12.2 3.7-13.5 3.8-13.6 4.0-14.5	6.3 6.8 7.0 7.4	134 160 164 188	100 130 140 180	12 14 15 17
6	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28-33	28 30 30.5 32	11 14 14 16	23 28 29 33	4.5-15.5 4.7-16.7 4.8-17.0 5.0-17.5	7.9 8.6 8.7 9.1	212 250 258 285	230 280 290 340	20 23 24 27

these situations. If scuba is used, a buddy line or other reference system and float are recommended. A convenient way to attach a buddy line is to use a rubber loop that can be slipped on and off the wrist easily, which is preferable to tying a line that cannot be removed rapidly. However, the line should not slip off so easily that it can be lost inadvertently.

Heavy concentrations of plankton often accumulate at the thermocline, especially during the summer and offshore of the mid-Atlantic states. Divers may find that plankton absorb most of the light at the thermocline and that even though the water below the thermocline is clear, a light is still necessary to see adequately. Thermoclines in clear water diffuse light within the area of greatest temperature change, causing a significant decrease in visibility.

Table 14-1
(Continued)

Sea-General		Wind				Sea						
						Wave Height Feet						
Sea State	Description	(Beaufort) Wind Force	Description	Range (Knots)	Wind Velocity (Knots)	Average	Average $\frac{1}{10}$ Highest	Significant Range of Periods (Seconds)	T (Average Period)	I (Average Wave Length)	Minimum Fetch (Nautical Miles)	Minimum Duration (Hours)
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	34 36 37 38 40	19 21 23 25 28	38 44 46.7 50 58	5.5-18.5 5.8-19.7 6-20.5 6.2-20.8 6.5-21.7	9.7 10.3 10.5 10.7 11.4	322 363 376 392 444	420 500 530 600 710	30 34 37 38 42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41-47	42 44 46	31 36 40	64 73 81	7-23 7-24.2 7-25	12.0 12.5 13.1	492 534 590	830 960 1110	47 52 57
9	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole Gale	48-55	48 50 51.5 52 54	44 49 52 54 59	90 99 106 110 121	7.5-26 7.5-27 8-28.2 8-28.5 8-29.5	13.8 14.3 14.7 14.8 15.4	650 700 736 750 810	1250 1420 1560 1610 1800	63 69 73 75 81
	Exceptionally high waves (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm	56-63	56 59.5	64 73	130 148	8.5-31 10-32	16.3 17.0	910 985	2100 2500	88 101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane	64-71	>64	>80	>164	10-(35)	(18)			

Source: US Navy (1985)

WARNING

Divers Should Be Extremely Cautious Around Wrecks or Other Structures in Low Visibility to Avoid Swimming Inadvertently Into an Area With Overhangs

A well-developed sense of touch is extremely important to divers or scientists working in low or zero underwater visibility. The ability to use touch cues when handling tools or instruments in a strange work environment is valuable to a diver in the dark. Rehearsing work functions on the surface while blindfolded will increase proficiency in underwater tasks.

Underwater low-light-level closed-circuit television has been used successfully when light levels are reduced, because a television camera "sees" more in these conditions than does the human eye. This is true mainly when the reduced visibility is caused by the absence of light; in cases where the problem is caused by high turbidity, a TV camera does not offer a significant advantage. When the purpose of the dive is inspection or observation and a closed-circuit television system is used, the diver serves essentially as a mobile underwater platform. The monitor is watched by surface support personnel who, in turn, direct the movements of the diver. Underwater television cameras are available that are either hand held or mounted on a helmet (see Section 8.14).

Divers are often required to dive in contaminated water that contains either waterborne or sediment-contained contaminants. The health hazards associated with polluted-water diving and the equipment to be used on such dives are described in Section 11.

14.2 DIVING SIGNALS

14.2.1 Hand Signals

Hand signals are used by divers to convey basic information. There are various hand signalling systems presently in use. Divers in different parts of the country and the world use different signals or variations of signals to transmit the same message. A set of signals used by NOAA is shown in Figure 14-2 and explained in Table 14-3. The signals consist of hand instead of finger motions so that divers wearing mittens can also use them. To the extent possible, the signals were derived from those having similar meanings on land. Before the dive, the dive master should review the signals shown in Figure 14-2 with all of the divers. This review is particularly important when divers from different geographical areas constitute a dive team or when divers from several organizations are cooperating in a dive. Signal systems other than hand signals have not been standardized; whistle blasts, light flashes, tank taps, and hand squeezes generally are used for attracting attention and should be reserved for that purpose.

14.2.2 Surface-to-Diver Recall Signals

Unexpected situations often arise that require divers to be called from the water. When voice communication is not available, the following methods should be considered:

- Acoustic Detonator (Firecracker)—a small device ignited by a flame and thrown into the water
- Hammer—rapping four times on a steel hull or metal plate
- Bell—held under water and struck four times
- Hydrophone—underwater speaker or sound beacon
- Strobe—used at night, flashed four times.

14.2.3 Line Signals

Divers using surface-supplied equipment use line signals either as a backup to voice communications to the surface or as a primary form of communication. Line signals also may be used by divers using self-contained equipment to communicate with the surface or, in conditions of restricted visibility, for diver-to-diver communications. Table 14-4 describes line signals commonly employed.

NOTE

Hand or line signals may vary by geographical area or among organizations. Divers should review signals before diving with new buddies or support personnel.

14.2.4 Surface Signals

If a diver needs to attract attention after surfacing and is beyond voice range, the following signaling devices may be used:

- Police whistle
- Flare
- Flashing strobe
- Flags (see Table 14-2).

14.3 AIR CONSUMPTION RATES

When considering diver air consumption rates, three terms need definition:

- Respiratory minute volume (RMV), the total volume of air moved in and out of the lungs in 1 minute;
- Actual cubic feet (acf)—the unit of measure that expresses actual gas volume in accordance with the General Gas Law; and
- Standard cubic feet (scf), the unit of measure expressing surface equivalent volume, under standard conditions,* for any given actual gas volume.

In computing a diver's air consumption rate, the basic determinant is the respiratory minute volume, which is directly related to the diver's exertion level and which, because of individual variation in physiological response, differs among divers (Cardone 1982). Physiological research has yielded useful estimates of respiratory

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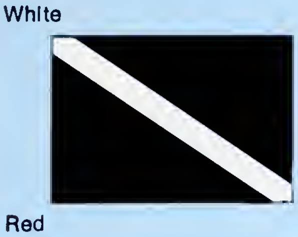
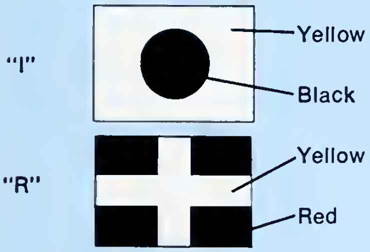
*Standard conditions for gases are defined as 32°F (0°C), 1 ATA pressure, and dry gas.

Table 14-2
Signal Flags, Shapes, and Lights

Signal	Use	Meaning
 Sport Diver Flag	Displayed by civilian divers in the United States. May be used with code flag alpha (flag A), but cannot be used in lieu of flag A. The Coast Guard recommends that the red-and-white diver's flag be exhibited on a float marking the location of the divers.	Divers are below. Boats should not operate within 100 feet. (Varies in accordance with individual state laws)
 International Code Flag "A"	Must be displayed by all vessels operating either in international waters or on the navigable waters of the United States that are unable to exhibit three shapes (see last row of this table). Flag A means that the maneuverability of the vessel is restricted.	"My maneuverability is restricted because I have a driver down; keep well clear at slow speed."
 International Code Flags "I R"[1]	Displayed by all vessels in international and foreign waters.	"I am engaged in submarine survey work (under water operations). Keep clear of me and go slow."
International Day Shapes and Lights 	Displayed by all vessels in international and foreign waters engaged in underwater operations.	This vessel is engaged in underwater operations and is unable to get out of the way of approaching vessels.

Derived from USCG *Navigation Rules: International/Inland* 1983, and *International Code of Signals*, United States Edition, 1981, published by the Defense Mapping Agency

Figure 14-2A
Hand Signals

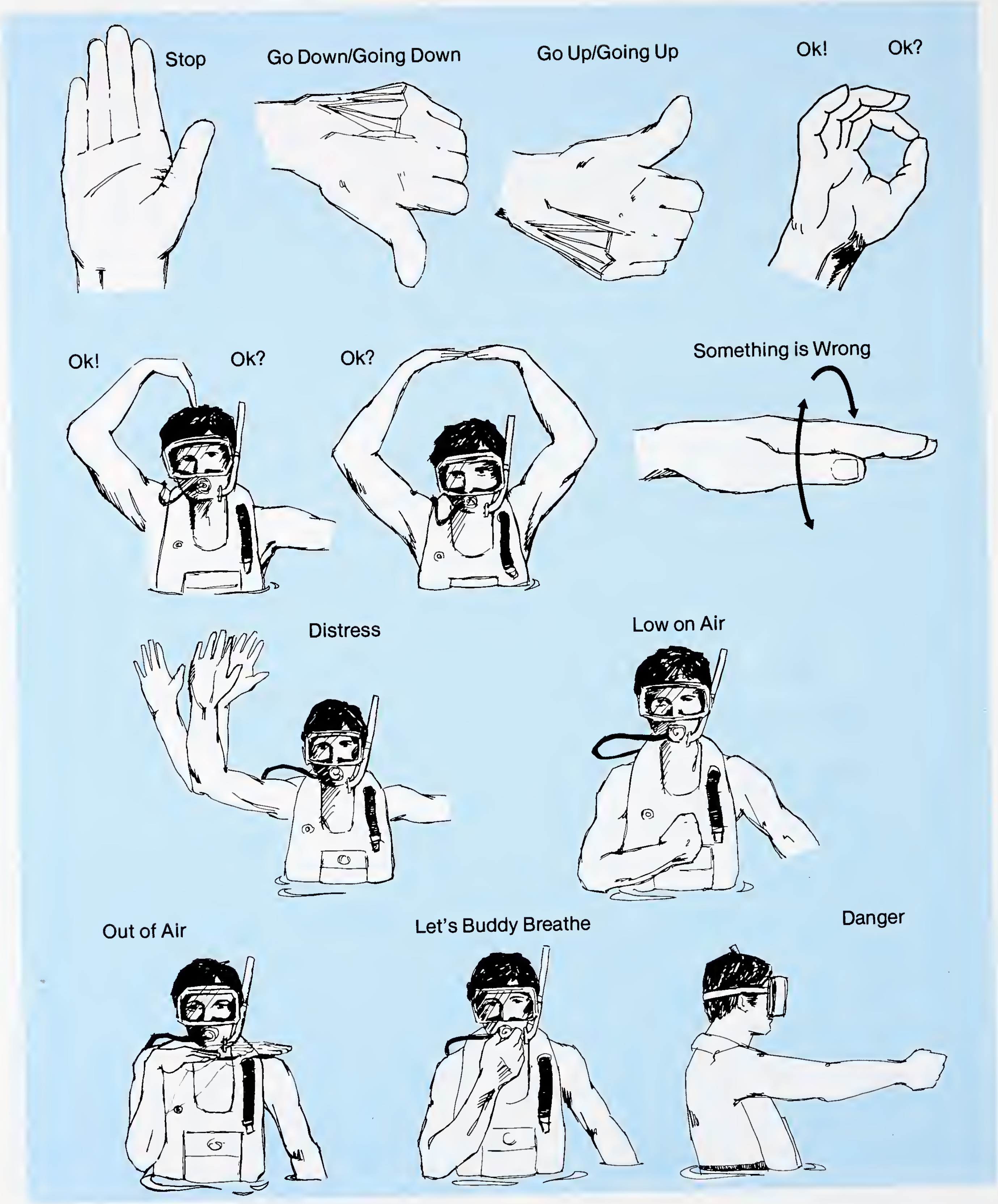
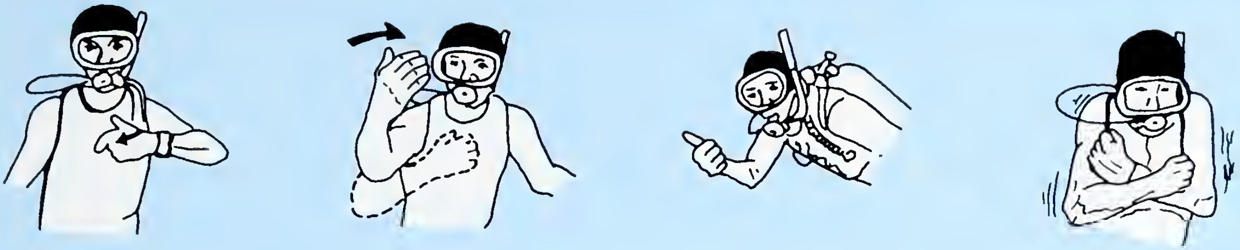


Figure 14-2B
Additional Hand Signals

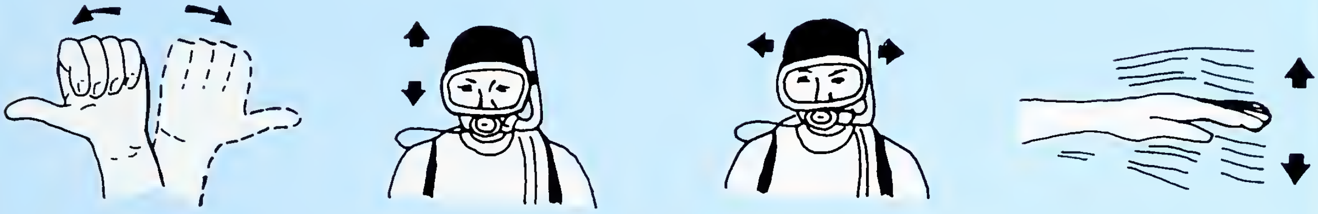


Me, or watch me

Come here

Go that way

I am cold

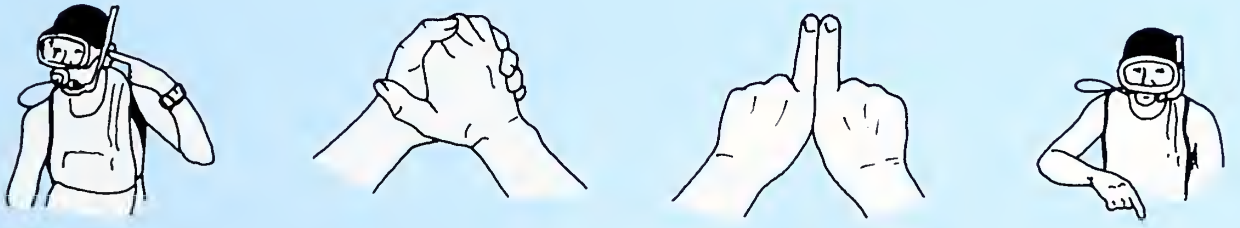


Which direction?

Yes

No

Take it easy, slow down



Ears not clearing

Hold hands

Get with your buddy

Look

You lead, I'll follow

What time? What depth?

I don't understand

Developed by American National Standards Institute Z86 Committee (1976)
in cooperation with the Council for National Cooperation in Aquatics

Table 14-3
Hand Signals

No.	Signal	Meaning	Comment
1.	Hand raised, fingers pointed up, palm to receiver	STOP	Transmitted in the same way as a Traffic Policeman's STOP
2.	Thumb extended downward from clenched fist	GO DOWN or GOING DOWN	
3.	Thumb extended upward from clenched fist	GO UP or GOING UP	
4.	Thumb and forefinger making a circle with 3 remaining fingers extended (if possible)	OK! or OK?	Divers wearing mittens may not be able to extend 3 remaining fingers distinctly (see both drawings of signal)
5.	Two arms extended overhead with fingertips touching above head to make a large O shape	OK! or OK?	A diver with only one free arm may make this signal by extending that arm overhead with fingertips touching top of head to make the O shape. Signal is for long-range use
6.	Hand flat, fingers together, palm down, thumb sticking out, then hand rocking back and forth on axis of forearm	SOMETHING IS WRONG	This is the opposite of OK! The signal does not indicate an emergency
7.	Hand waving over head (may also thrash hand on water)	DISTRESS	Indicates immediate aid required
8.	Fist pounding on chest	LOW ON AIR	Indicates signaller's air supply is reduced to the quantity agreed upon in predive planning or air pressure is low and has activated reserve valve
9.	Hand slashing or chopping throat	OUT OF AIR	Indicates that signaller cannot breathe
10.	Fingers pointing to mouth	LET'S BUDDY BREATHE	The regulator may be either in or out of the mouth
11.	Clenched fist on arm extended in direction of danger	DANGER	

All signals are to be answered by the receiver's repeating the signal as sent. When answering signals 7, 9, and 10, the receiver should approach and offer aid to the signaller.

Source: NOAA (1979)

minute volumes for typical underwater situations likely to be encountered by most divers (US Navy 1985). Table 14-5 shows these estimates. These estimates of respiratory minute volumes apply to any depth and are expressed in terms of actual cubic feet, or liters, per minute (acfm or alpm, respectively).

The consumption rate at depth can be estimated by determining the appropriate respiratory minute volume for the anticipated exertion level and the absolute pressure of the anticipated dive depth. This estimate, expressed in standard cubic feet per minute (scfm), is given by the equation:

$$Cd = RMV (Pa)$$

where Cd = consumption rate at depth in scfm; RMV = respiratory minute volume in acfm; and Pa = absolute pressure (ATA) at dive depth.

Problem:

Compute a diver's air consumption rate for a 50 fsw (15.2 m) dive requiring moderate work.

Solution:

$$Cd = RMV (Pa)$$

RMV = 1.1 acfm (from Table 14-5); $Pa = 50/33 + 1 = 2.51$ ATA; and $Cd = (1.1)(2.51) = 2.76$ scfm.

14.3.1 Determining Individual Air Utilization Rates

An alternative approach that can be used by individual divers expresses air utilization rates in terms of pressure drop in pounds per square inch (psi) rather than respiratory minute volume, keeping in mind that usable tank pressure is defined as the beginning tank pressure minus recommended air reserve (see Table 14-8). This technique allows divers to make a timed swim at one particular depth once they have determined their individual air utilization rate. To determine their rate, divers must read their submersible pressure gauges at the beginning and end of a dive to a

Table 14-4
Line Pull Signals for
Surface-to-Diver Communication

Emergency Signals

2-2-2 Pulls	"I am fouled and need the assistance of another diver"
3-3-3 Pulls	"I am fouled but can clear myself"
4-4-4 Pulls	"Haul me up immediately"

All signals will be answered as given except for emergency signal 4-4-4

From tender to diver

1 Pull	"Are you all right?" When diver is descending, one pull means "stop"
2 Pulls	"Going down" During ascent, 2 pulls mean "You have come up too far, go back down until we stop you"
3 Pulls	"Stand by to come up"
4 Pulls	"Come up"
2-1 Pulls	"I understand," or "Answer the telephone"

From diver to tender

1 Pull	"I am all right" or "I am on the bottom"
2 Pulls	"Lower" or "Give me slack"
3 Pulls	"Take up my slack"
4 Pulls	"Haul me up"
2-1 Pulls	"I understand" or "Answer the telephone"
3-2 Pulls	"More air"
4-3 Pulls	"Less air"

Special signals from the diver to the tender should be devised as required by the situation

Searching Signals	**Without circling line**	**With circling line**
7 Pulls	"Go on (or off) searching signals"	Same
1 Pull	"Stop and search where you are"	Same
2 Pulls	"Move directly away from the tender if given slack, move toward the tender if strain is taken on the life-line"	"Move away from the weight"
3 Pulls	"Go to your right"	"Face the weight and go right"
4 Pulls	"Go to your left"	"Face the weight and go left"

Source: NOAA (1979)

constant depth. These readings give them the information needed to use the simple 4-step procedure shown below.

(1) Subtract ending psi (as read from the submersible pressure gauge) from the beginning psi to determine the amount of air used during the timed dive (Δ psi);

(2) Using the following formula, estimate air utilization rate on the surface:

$$\frac{\Delta\text{ psi/time (min)}}{(\text{depth in ft} + 33)/33} = \text{psi per minute on the surface;}$$

(3) Find the psi per minute on the surface on the left side of the Air Utilization Table (Table 14-6) that is closest to your estimated psi per minute. Read across until you come to the desired depth, which will give you your estimated air utilization rate;

(4) To estimate how many minutes your tank of air will last at that depth, divide the number of usable psi in the tank (as shown on your submersible pressure gauge) by the psi per minute used at that depth.

Problem:

A diver swims a distance at 30 fsw (9 m) in 10 minutes; the submersible pressure gauge reads 2350 psi at the start and 2050 at the end of the timed dive, showing that a total of 300 psi was consumed. What is the diver's air utilization?

The basic equation is:

$$\frac{\Delta\text{ psi/time (min)}}{(\text{depth in ft} + 33)/33}$$

Solution:

$$\frac{300\text{ (psi)} \div 10\text{ (minutes)}}{\frac{30\text{ (depth)} + 33}{33}} = \frac{30}{\frac{63}{33}} = \frac{30}{1.9} = 15.7\text{ psi/min.}$$

The diver would consume 15.7 psi per minute at the surface. Knowing your utilization rate at the surface allows you to use Table 14-6 to find your rate at any depth.

Air utilization rates determined by this method are valid only for air coming from the same type of tank as that used on the timed swim. Further, individuals vary somewhat from day to day in their air utilization rates, and these calculations should thus be considered estimates only (Cardone 1982).

14.4 SELF-CONTAINED DIVING

14.4.1 Scuba Duration

Knowing the probable duration of the scuba air supply is vital to proper dive planning. With scuba, the duration of the available air supply is directly depend-

Table 14-5
Respiratory Minute Volume (RMV)
at Different Work Rates

	Activity	Respiratory Minute Volume	
		Actual liters/min (STP)	Actual cubic ft/min (STP)
REST	Bed rest (basal)	5	0.18
	Sitting quietly	6	0.21
	Standing still	8	0.28
LIGHT WORK	SLOW WALKING ON HARD BOTTOM	12	0.42
	Walking, 2 mph	14	0.49
	SWIMMING, 0.5 KNOT (SLOW)	16	0.60
MODERATE WORK	SLOW WALKING ON MUD BOTTOM	20	0.71
	Walking, 4 mph	24	0.85
	SWIMMING, 0.85 knot (av. speed)	26	0.92
	MAX. WALKING SPEED, HARD BOTTOM	30	1.1
HEAVY WORK	SWIMMING, 1.0 KNOT	35	1.2
	MAX. WALKING SPEED, MUD BOTTOM	35	1.2
	Running, 8 mph	44	1.5
SEVERE WORK	SWIMMING, 1.2 KNOTS	53	1.9
	Uphill running	84	2.9

Underwater activities are in capitals.

Adapted from US Navy (1985)

ent on the diver's consumption rate. Scuba air supply duration can be estimated using the equation:

$$Da = \frac{Va}{Cd}$$

where Da = duration in min; Va = available volume in scf; and Cd = consumption at depth in scfm.

The available volume depends on the type (rated volume and rated pressure) and number of cylinders used, the gauge pressure measured, and the recommended minimum cylinder pressure. The diver's air consumption rate depends on the depth and the exertion level of the dive.

The "standard 72" steel scuba cylinder has an internal volume of 0.423 ft^3 (11.98 L) at 1 ATA. At its rated pressure (2475 psig), the cylinder contains a deliverable volume of 71.2 ft^3 (2016 L).

For a given scuba cylinder, the ratio of rated volume to rated pressure is a constant, meaning that a constant volume of air is delivered for each unit of cylinder pressure drop. Mathematically, this results in a linear relationship between gauge pressure and deliverable volume. Figure 14-3 shows this relationship for a 71.2 ft^3 (2016 L) steel cylinder and an 80 ft^3 (2266 L) aluminum cylinder. Deliverable volumes at any gauge pressure for these two cylinder types can be read directly from Figure 14-3, or they can be individually computed using the equation

$$Vd = Pgk$$

where Vd = deliverable volume in scf; Pg = gauge pressure in psig; and k = cylinder constant. This equation can be used for any type of cylinder; see Table 14-7 for the appropriate cylinder constant.

For planning purposes, the available volume of air is the difference between the deliverable volume at a given cylinder pressure and the recommended minimum cylinder pressure. The recommended minimum cylinder pressures for the two most commonly used scuba cylinder types are shown in Table 14-8. The available volume of air in a diver's supply is given by the equation

$$Va = N(Pg - Pm)k$$

where Va = available volume in scf; N = number of cylinders; Pg = gauge pressure in psig; Pm = recommended minimum pressure in psig; and k = cylinder constant. For planning purposes, estimates of cylinder duration are based on available air volumes rather than deliverable air volumes.

Table 14-6
Air Utilization Table at Depth

DEPTH IN FEET

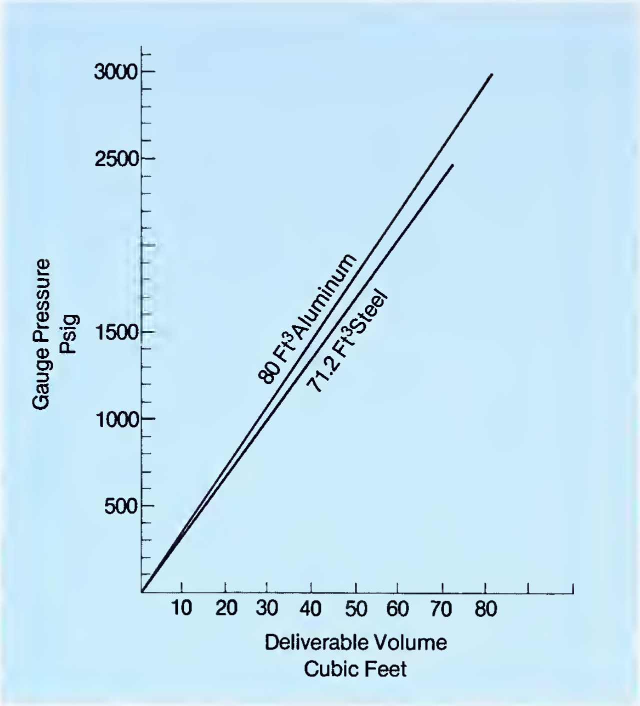
UTILIZATION RATE AT SURFACE (PSI PER MINUTE)

Surface	10	15	20	25	30	40	50	60	70	80	90	100	120	140	160
15	19.5	21.8	24.0	27.0	28.5	33.0	37.5	42.0	46.5	51.0	55.5	60.0	69.0	78.0	87.0
16	20.8	23.2	25.6	28.8	30.4	35.2	40.0	44.8	49.6	54.4	59.2	64.0	73.6	83.2	92.8
17	22.1	24.7	27.2	30.6	32.3	37.4	42.5	47.6	52.7	57.8	62.9	68.0	78.2	88.0	98.6
18	23.4	26.1	28.8	32.4	34.2	39.6	45.0	50.4	55.8	61.2	66.6	72.0	82.8	93.6	104.4
19	24.7	27.6	30.4	34.2	36.1	41.8	47.5	53.2	58.9	64.6	70.3	76.0	87.4	98.8	110.2
20	26.0	29.0	32.0	36.0	38.0	44.0	50.0	56.0	62.0	68.0	74.0	80.0	92.0	104.0	116.0
21	27.3	30.5	33.6	37.8	39.9	46.2	52.5	58.8	65.1	71.4	77.7	84.0	96.6	109.2	121.8
22	28.6	31.9	35.2	39.6	41.8	48.4	55.0	61.6	68.2	74.8	81.4	88.0	101.2	114.4	127.6
23	29.9	33.4	36.8	41.4	43.7	50.6	57.5	64.4	71.3	78.2	85.1	92.0	105.8	119.6	133.4
24	31.2	34.8	38.4	43.2	45.6	52.8	60.0	67.2	74.4	81.6	88.8	96.0	110.4	124.8	139.2
25	32.5	36.3	40.0	45.0	47.5	55.0	62.5	70.0	77.5	85.0	92.5	100.0	115.0	130.0	145.0
26	33.8	37.7	41.6	46.8	49.4	57.2	65.0	72.8	80.6	88.4	96.2	104.0	119.6	135.2	150.8
27	35.1	39.2	43.2	48.6	51.3	59.4	67.5	75.6	83.7	91.8	99.9	108.0	124.2	140.4	156.6
28	36.4	40.6	44.8	50.4	53.2	61.6	70.0	78.4	86.8	95.2	103.6	112.0	128.8	145.6	162.4
29	37.7	42.1	46.4	52.2	55.1	63.8	72.5	81.2	89.9	98.6	107.3	116.0	133.4	150.8	168.2
30	39.0	43.5	48.0	54.0	57.0	66.0	75.0	84.0	93.0	102.0	111.0	120.0	138.0	156.0	174.0
31	40.3	45.0	49.6	55.8	58.9	68.2	77.5	86.8	96.1	105.4	114.7	124.0	142.6	161.2	179.8
32	41.6	46.4	51.2	57.6	60.8	70.4	80.0	89.6	99.2	108.8	118.4	128.0	147.2	166.4	185.6
33	42.9	47.9	52.8	59.4	62.7	72.6	82.5	92.4	102.3	112.2	122.1	132.0	151.8	171.6	191.4
34	44.2	49.3	54.4	61.2	64.6	74.8	85.0	95.2	105.4	115.6	125.8	136.0	156.4	176.8	197.2
35	45.5	50.8	56.0	63.0	66.5	77.0	87.5	98.0	108.5	119.0	129.5	140.0	161.0	182.0	203.0
36	46.8	52.2	57.6	64.8	68.4	79.2	90.0	100.8	111.6	122.4	133.2	144.0	165.6	187.2	208.8
37	48.1	53.7	59.2	66.6	70.3	81.4	92.5	103.6	114.7	125.8	136.9	148.0	170.2	192.4	214.6
38	49.4	55.1	60.8	68.4	72.2	83.6	95.0	106.4	117.8	129.2	140.6	152.0	174.8	197.6	220.4
39	50.7	56.6	62.4	70.2	74.1	85.8	97.5	109.2	120.9	132.6	144.3	156.0	179.4	202.8	226.2
40	52.0	58.0	64.0	72.0	76.0	88.0	100.0	112.0	124.0	136.0	148.0	160.0	184.0	208.0	232.0

See Section 14.3.1 for table use instructions.

Derived from *Jeppeson Sport Diver Manual*
See Section 14.3.1 for table use instructions

Figure 14-3
Deliverable Volumes
at Various Gauge Pressures



Source: NOAA (1979)

Problem:

Estimate the duration of a set of twin 80 ft^3 (2266 L) aluminum cylinders charged to 2400 psig for a 70 fsw (21.3 m) dive requiring the diver to swim at 0.5 knot (0.25 m/s).

Solution:

The basic equation for duration is

$$\text{Da} = \frac{\text{Va}}{\text{Cd}}$$

where Da = duration in minutes; Va = available volume in scf; and Cd = consumption rate at depth in scfm.

Step 1

Determine Va using

$$\begin{aligned} \text{Va} &= \text{N(Pg} - \text{Pm)k} \\ \text{Va} &= 2(2400 \text{ psig} - 600 \text{ psig})\ (0.0266 \text{ scf/psig}) \\ &= 2(1800 \text{ psig})\ (0.0266 \text{ scf/psig}) \\ &= 95.76 \text{ scf.} \end{aligned}$$

Step 2

Determine Cd using

$$\text{Cd} = \text{RMV (Pa)}$$

Table 14-7
Cylinder Constants

Rated Volume (scf)	Working Pressure (psig)	Rated Pressure (psig)	Cylinder Constant
	Aluminum		
90	3000	3000	0.0300
80	3000	3000	0.0266
71.2	3000	3000	0.0237
50.0	3000	3000	0.0166
	Steel		
100	2400	2640	0.0378
71.2	2250	2475	0.0288
52.8	1800	1980	0.0267
50.0	2250	2475	0.0202
42.0	1880	2068	0.0203
38.0	1800	1980	0.0192

Adapted from NOAA (1979)

where RMV = respiratory minute volume in acfm; Pa = absolute pressure at dive depth.

$$\begin{aligned} \text{Cd} &= 0.6 \text{ acfm} \left(\frac{70}{33} + 1\right) \\ &= 1.87 \text{ scfm.} \end{aligned}$$

Step 3

Solve the basic equation for Da

$$\begin{aligned} \text{Da} &= \frac{\text{Va}}{\text{Cd}} \\ &= \frac{95.76 \text{ scf}}{1.87 \text{ scfm}} \\ &= 51.2 \text{ minutes.} \end{aligned}$$

Table 14-9 shows estimates of the duration of a single steel 71.2 ft^3 (2016 L) cylinder at five exertion levels for various depths. These estimated durations are computed on the basis of an available air volume of 58.9 ft^3 (Va = 2475 psig − 430 psig) (0.0288 ft^3/psig).

14.4.2 Scuba Air Requirements

Total air requirements should be estimated when planning scuba operations. Factors that influence the total air requirement are depth of the dive, anticipated bottom time, normal ascent time at 60 ft/min (18.3 m/min), any required stage decompression time, and consumption rate at depth. For dives in which direct ascent to the surface at 60 ft/min (18.3 m/min) is allowable, the total air requirement can be estimated using the equation

$$\text{TAR} = \text{tdt (Cd)}$$

where TAR = total air requirement in scf; tdt = total dive time in minutes (bottom time plus ascent time at

Table 14-8
Scuba Cylinder
Pressure Data

Cylinder Type	Rated Pressure (psig)	Working Pressure (psig)	Reserve Pressure (psig)	Recommended Minimum Pressure (psig)
Steel 72	2475	2250	500	430
Aluminum 80	3000	3000	500	600

Source: NOAA (1979)

Table 14-9
Estimated Duration of
71.2 ft^3 Steel Cylinder

		RMV				
Depth	ATA	0.25 acfm At Rest	0.7 acfm Light Work	1.1 acfm Moderate Work	1.5 acfm Heavy Work	2.2 acfm Severe Work
0	1.0	235.6	84.1	53.5	39.3	26.8
33	2.0	117.9	42.1	26.8	19.6	13.4
66	3.0	78.5	28.0	17.8	13.1	8.9
99	4.0	58.9	21.0	13.4	9.8	6.7
132	5.0	47.1	16.8	10.7	7.8	5.4
165	6.0	39.3	14.0	8.9	6.5	4.4

Values are minutes.

Source: NOAA (1979)

60 ft/min); and Cd = consumption rate at depth in scfm.

Problem:

Estimate the total air requirements for a 30-minute dive to 60 fsw (18.3 m) involving swimming at 0.85 knot (0.43 m/s).

Solution:

Step 1

Determine tdt. Total dive time is defined as the sum of the bottom time and normal ascent time at 60 ft/min (18.3 m/min):

$$\text{tdt} = 30 + 1 = 31 \text{ minutes.}$$

Step 2

Determine Cd using the equation

$$\begin{aligned} \text{Cd} &= \text{RMV (Pa)} \\ \text{RMV} &= 0.92 \text{ acfm (from Table 14-5)} \\ \text{Pa} &= \frac{60}{33} + 1 = 2.81 \text{ ATA} \\ \text{Cd} &= (0.92 \text{ acfm})(2.81 \text{ ATA}) \\ &= 2.59 \text{ scfm.} \end{aligned}$$

Step 3

Determine TAR using the equation

$$\begin{aligned} \text{TAR} &= \text{tdt (Cd)} \\ &= (31 \text{ min})(2.59 \text{ acfm}) \\ &= 80.37 \text{ scf.} \end{aligned}$$

For dives in which stage decompression will be necessary, the total air requirement can be estimated using the equation

$$\text{TAR} = \text{Cd (BT + AT)} + \text{Cd}_1\text{T}_1 + \text{Cd}_2\text{T}_2 + \text{Cd}_3\text{T}_3 \text{ (etc.)}$$

where Cd_1T_1, Cd_2T_2, and Cd_3T_3 are the air consumption rates and times at the respective decompression stops.

Problem:

Estimate the total air requirement for a 60-minute dive to 70 fsw (21.3 m) requiring the diver to swim at 0.5 knot (0.25 m/s).

Solution:

Step 1

Determine Cd and Cd_1 using the equation

$$\begin{aligned} \text{Cd} &= \text{RMV (Pa)} \\ &= (0.6 \text{ acfm})(3.12 \text{ ATA}) \\ &= 1.87 \text{ scfm.} \end{aligned}$$

Step 2

Determine the total time for the dive, ascent, and decompression stops. For the dive and ascent to the first decompression stop, add the bottom time and the ascent time (to the nearest whole minute) to the first decompression stop at 60 ft/min (18.3 m/min).

$$BT + AT = 60 + 1 = 61 \text{ minutes.}$$

This dive requires a 10-foot decompression stop. At an ascent rate of 60 ft/min, it will take 1 minute to ascend from 70 feet (21.3 m) to 10 feet (3 m).

The time required for decompression at 10 feet (3 m) is 8 minutes, according to the Air Decompression Table (US Navy 1985) for a dive to 70 feet for 60 minutes.

$$Cd_1 = 0.6\left(\frac{10}{33} + 1\right) = 0.78 \text{ scfm}$$

(Assume light work (0.6 acfm) on decompression stop.)

Step 3

Determine TAR using the equation for this case

$$\begin{aligned} TAR &= Cd\,(BT + AT) + Cd_1T_1 \\ &= (1.87 \text{ scfm})\,(61 \text{ min}) + (0.78 \text{ scfm})\,(8 \text{ min}) \\ &= 114.1 + 6.2 = 120.3 \text{ scf.} \end{aligned}$$

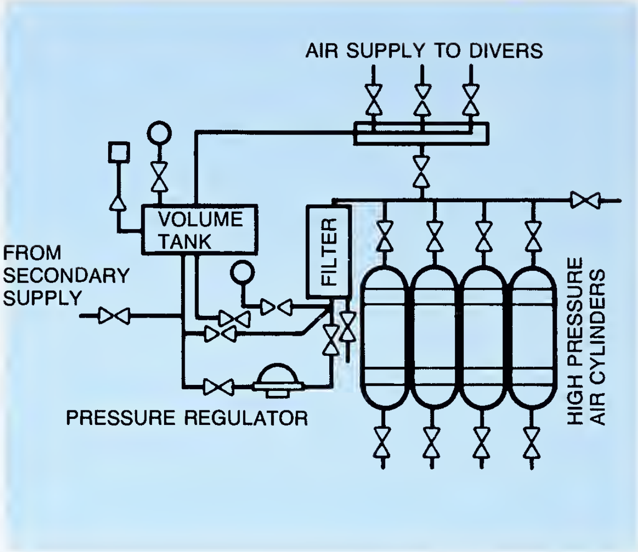
Computation of these estimates during predive planning is useful to decide whether changes in assigned tasks, task planning, etc. are necessary to ensure that the dive can be conducted with the available air supply. However, positioning an auxiliary tank at the decompression stop is considered a safer practice than relying on calculations of the available air supply.

14.5 HIGH-PRESSURE AIR STORAGE SYSTEMS

For most scientific surface-supplied diving operations, a high-pressure air storage system is better than a low-pressure compressor system. In some cases, the size of the surface support platform dictates the use of the simpler and more compact low-pressure compressor system. A high-pressure system can be tailored conveniently to the requirements of a particular operation, is easier to handle than the other type of system, and offers the additional advantage of reduced noise and improved communication. The planning factors that influence the configuration of a high-pressure air storage system include:

- Depth of the planned dive
- Number of divers to be supplied and the anticipated exertion level
- Type of breathing apparatus (free flow or demand)
- Size of the surface support platform.

Figure 14-4
Typical High Pressure Cylinder
Bank Air Supply



Source: US Navy (1985)

A complete system includes high-pressure cylinders (200-350 standard ft^3 size), the necessary piping and manifolds, a pressure reduction regulator, and a volume cylinder (at least 1 ft^3 volume) (Figure 14-4). A high-pressure filter should always be incorporated into or be located just upstream of each pressure regulator. Filter elements should be of the woven-metal cloth type and should have a collapse pressure rating greater than the maximum possible pressure differential. A high-pressure gauge must be located ahead of the pressure reduction regulator, and a low-pressure gauge must be connected to the volume cylinder. The volume cylinder must be fitted with an overpressure relief valve. A manually controlled regulator by-pass valve or a redundant regulator with its own filter also should be included in the system.

NOTE

If cylinder banks are used to back up a compressor supply, the bank must be manifolded with the primary source so that an immediate switch from primary to secondary air is possible.

System Capacity and Air Supply Requirements

Estimations of air supply requirements and duration of air supplies for surface-supplied divers are the same as those of scuba divers (Section 14.4.2) except when free-flow or free-flow/demand breathing systems are used; in these cases, the flow, in acfm, is used (in all calculations) instead of RMV (see Table 14-5 and Table 14-10). Also, the minimum bank pressure must be calculated to be equal to 220 psig plus the absolute pressure of the dive (expressed in psia).

Problem:

Estimate the air requirements for a 90 fsw (27 m) dive for 70 min with a free-flow helmet. This dive requires decompression stops of 7 minutes at 20 feet (6.1 m) and 30 minutes at 10 feet (3 m).

$$TAR = Cd\,(BT + AT) + Cd_1T_1 + Cd_2T_2.$$

Step 1

Determine Cd, Cd_1, Cd_2

$$\begin{aligned} Cd &= \text{flow x Pa} \\ &= (6\text{ acfm})(3.73\text{ ATA}) = 22.4\text{ scfm} \\ Cd_1 &= (6\text{ acfm})(1.61\text{ ATA}) = 9.7\text{ scfm} \\ Cd_2 &= (6\text{ acfm})(1.30\text{ ATA}) = 7.8\text{ scfm.} \end{aligned}$$

Step 2

$$\begin{aligned} TAR &= 22.4\,(70 + 1.2) + 9.7\,(7) + 7.8\,(30) \\ &= 1595 + 67.9 + 234 \\ &= 1897\text{ scf.} \end{aligned}$$

Cylinder constants for large high-pressure air storage systems are determined in the same fashion as those for scuba cylinders, i.e., rated volume/rated pressure = k.

The procedure for determining available volume of air is also the same as for scuba. For example,

$$Va = N(Pg - Pm)\,k.$$

Problem:

Determine the number of high-pressure air cylinders required to supply the air for the above dive (1897 scf) if the rated volume equals 240 scf, rated pressure equals 2400 psi, and beginning pressure equals 2000 psi.

Step 1

How much air could be delivered from each cylinder?

$$Va = N(Pg - Pm)\,k$$

$$k = \frac{240\text{ scf}}{2400\text{ psi}} = 0.1\text{ scf/psi}$$

$$Pm = 220\text{ psi} + \left(\frac{90 + 33}{33} \times 14.7\right)$$

$$Va = 1(2000 - 275) \times 0.1$$

$$Va = 172.5\text{ scf/cylinder.}$$

Table 14-10
Flow-Rate Requirements
for Surface-Supplied Equipment

Equipment Type	Flow Rate
Free flow/demand	1.5 acfm
Free flow	6.0 acfm

NOTE: Significant variations in these values can occur, depending on the flow-valve set by the diver. Therefore, these values are minimum estimates.

Source: Morgan Wells

Step 2

How many cylinders would be required in the bank to supply the required amount of gas?

$$N = \frac{\text{vol. required}}{\text{vol/cyl}} = \frac{1897\text{ scf}}{172.5\text{ scf/cyl}} = 10.9\text{ or }11\text{ cylinders.}$$

14.6 DECOMPRESSION ASPECTS OF AIR DIVING

The principal inert gas in air is nitrogen. The role of nitrogen in the physiological processes of inert gas absorption and elimination and its role in decompression sickness are discussed in detail in Sections 3 and 20. When air is breathed under pressure, the inert nitrogen diffuses into the various tissues of the body. Nitrogen uptake by the body continues, at different rates for the various tissues, as long as the partial pressure of the inspired nitrogen is higher than the partial pressure of the gas absorbed in the tissues. Consequently, the amount of nitrogen absorbed increases as the partial pressure of the inspired nitrogen (depth) and the duration of the exposure (time) increases.

When the diver begins to ascend, the process is reversed because the nitrogen partial pressure in the tissues exceeds that in the circulatory and respiratory systems. If the partial pressure of nitrogen in the blood significantly exceeds ambient pressure, bubbles can form in the tissues and blood, causing decompression sickness.

To prevent the development of decompression sickness, several decompression tables have been developed. These tables take into consideration the amount of nitrogen absorbed by the body at various depths for given time periods. They also consider allowable pressure gradients that can exist without excessive bubble formation and the different gas elimination rates associated with various body tissues.

Stage decompression, which involves stops of specific durations at given depths, is used for air diving because of its operational simplicity. The decompression tables require longer stops at more frequent intervals as the surface is approached because of the higher gas expansion ratios at shallow depths.

A basic understanding of the use of these decompression tables is essential to the safety of a diving operation. The constraints these tables and procedures impose on the conduct of air diving operations must always be a factor in dive planning.

14.6.1 Definitions

The definitions of some terms used frequently in discussing the decompression aspects of air diving (which are defined in the glossary) are:

Depth—The maximum depth attained during the dive, measured in feet of seawater (fsw)

Total bottom time—The total elapsed time starting when the diver leaves the surface to the time (next whole minute) that ascent begins (in minutes)

Decompression stop—The designated depth and time at which a diver must stop and wait during ascent from a decompression dive; the depth and time are specified by the decompression schedule used

Decompression schedule—A set of depth-time relationships and instructions for controlling pressure reduction

Normal ascent rate—60 feet per minute (18.3 m/min)

No-decompression dive—A dive from which a diver can return directly to the surface at a controlled rate without spending time at shallower depths to allow inert gas to be eliminated from the body

Decompression dive—Any dive involving a depth deep enough or a duration long enough to require controlled decompression; any dive in which ascent to the surface must be carried out through decompression stops

Single dive—Any dive conducted no less than 12 hours or more after a previous dive by the same diver

Residual nitrogen—A theoretical concept that describes the amount of nitrogen remaining in a diver's tissues after a hyperbaric exposure

Surface interval—The elapsed time between surfacing from the dive and the time when the diver leaves the surface for the next dive

Repetitive dive—Any dive conducted within 12 hours of a previous dive

Repetitive group designation—A letter that is used in decompression tables to designate the amount of residual nitrogen in a diver's body for a 12-hour period after a dive

Residual nitrogen time—Time (in minutes) added to actual bottom time for calculating the decompression schedule for a repetitive dive, based on the concept of residual nitrogen

Equivalent single dive bottom time—A dive for which the bottom time used to select the decompression schedule is the sum of the residual nitrogen time and the actual bottom time of the dive

Exceptional exposure dives—Any dive in which the diver is exposed to oxygen partial pressures, environmental conditions, or bottom times considered to be extreme.

14.6.2 Air Decompression Tables and Their Applications

In the conduct of normal operations, two dive tables are commonly used. These tables are:

- U.S. Navy No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Air Dives (also called the No-Decompression Table) (see Table 14-11).
- U.S. Navy Standard Air Decompression Table (also called the Standard Air Table) (see Appendix B).

For non-saturation air dives, these two tables cover every possible decompression schedule required in routine diving. Except under the guidance of qualified diving medical personnel in emergency situations, these tables must be followed to ensure maximum diving safety. In repetitive diving situations, these tables are supplemented by the U.S. Navy Residual Nitrogen Timetable for Repetitive Air Dives (also called the Repetitive Dive Table) (see Table 14-12), which is a planning aid, not a decompression table.

Whether a dive is a decompression or a no-decompression dive, the use of these decompression tables involves observing the following instructions.

- All dives that are not separately listed are covered in the tables by the next deeper and next longer schedule; DO NOT INTERPOLATE
- Enter the tables at the listed depth that is exactly equal to, or is the next greater depth than, the maximum depth attained during the dive
- Select the bottom time of the bottom times listed for the selected depth that is exactly equal to, or is next greater than, the bottom time of the dive

Table 14-11
No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Air Dives

Depth (feet)	No-decompression limits (min)	Repetitive Group Designation														
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
10		60	120	210	300											
15		35	70	110	160	225	350									
20		25	50	75	100	135	180	240	325							
25		20	35	55	75	100	125	160	195	245	315					
30		15	30	45	60	75	95	120	145	170	205	250	310			
35	310	5	15	25	40	50	60	80	100	120	140	160	190	220	270	310
40	200	5	15	25	30	40	50	70	80	100	110	130	150	170	200	
50	100		10	15	25	30	40	50	60	70	80	90	100			
60	60		10	15	20	25	30	40	50	55	60					
70	50		5	10	15	20	30	35	40	45	50					
80	40		5	10	15	20	25	30	35	40						
90	30		5	10	12	15	20	25	30							
100	25		5	7	10	15	20	22	25							
110	20			5	10	13	15	20								
120	15			5	10	12	15									
130	10			5	8	10										
140	10			5	7	10										
150	5			5												
160	5				5											
170	5				5											
180	5				5											
190	5				5											

Source: US Navy (1985)

- Use the decompression stops listed on the line for the selected bottom time
- Ensure that the level of the diver's chest is kept as close as possible to each decompression depth for the number of minutes listed
- Commence timing each stop on arrival and resume ascent when specified time has elapsed. Do not include ascent time as part of stop time
- Observe all special table instructions
- Always fill out a Repetitive Dive Worksheet or a similar systematic guideline.

When using the decompression tables, a normal ascent rate is necessary. If for some reason the normal ascent rate cannot be maintained, the decompression schedule must be modified as follows:

- If the delay was at a depth greater than 50 feet (15.2 m), increase the bottom time of the dive by the difference between the time used in ascent and the time that should have been used at a rate of 60 feet/minute (18.3 m/min); decompress according to the requirements of the new total bottom time
- If the delay was at a depth less than 50 feet (15.2 m), increase the first stop by the difference between the time used in ascent and the time that should have been used at the rate of 60 feet/minute (18.3 m/min).

14.6.2.1 No-Decompression Limits and Repetitive Group Designation Tables for No-Decompression Air Dives

The No-Decompression Table (Table 14-11) serves two purposes. First, it summarizes all the depth and bottom time combinations for which no decompression is required. Second, it provides the repetitive group designation for each no-decompression dive. Although decompression is not required, an amount of nitrogen remains in the diver's tissues after every dive. For additional dives within a 12-hour period, the diver must consider this residual nitrogen when calculating his or her decompression requirements.

Each depth listed in the No-Decompression Table has a corresponding no-decompression limit given in minutes. This limit is the maximum bottom time that a diver may spend at that depth without requiring decompression. The columns to the right of the no-decompression limits column are used to determine the repetitive group designation that must be assigned to a diver after every dive. Dives to depths shallower than 35 feet (10 meters) do not have a specific no-decompression limit. However, such dives are restricted in that they provide repetitive group designations only for bottom times of between 5 and 6 hours. These bottom times are considered the limitations of the

Table 14-12
Residual Nitrogen Timetable
for Repetitive Air Dives

*Dives after surface intervals of more than 12 hours are not repetitive dives. Use actual bottom times in the Standard Air Decompression Tables to compute decompression for such dives. See section 14.6.2.3 for instructions in the use of this table.

Repetitive group at the beginning of the surface interval

A																0.10 12:00*
B															0:10 2:10	2:11 12:00*
C														0:10 1.39	1:40 2:49	2:50 12:00*
D													0:10 1:09	1:10 2:38	2:39 5:48	5:49 12:00*
E												0:10 0.54	0:55 1:57	1:58 3:22	3:23 6:32	6:33 12:00*
F											0:10 0:45	0:46 1:29	1:30 2:28	2:29 3:57	3:58 7:05	7:06 12:00*
G										0:10 0:40	0:41 1 15	1:16 1:59	2:00 2:58	2:59 4:25	4:26 7:35	7:36 12:00*
H									0:10 0:36	0:37 1:06	1:07 1:41	1:42 2:23	2:24 3:20	3:21 4.49	4:50 7:59	8:00 12:00*
I								0:10 0:33	0:34 0:59	1:00 1:29	1:30 2:02	2 03 2:44	2:45 3:43	3.44 5:12	5.13 8:21	8:22 12:00*
J							0:10 0:31	0:32 0:54	0:55 1:19	1:20 1:47	1:48 2:20	2:21 3 04	3:05 4:02	4 03 5.40	5:41 8:40	8:41 12:00*
K						0:10 0:28	0:29 0:49	0:50 1.11	1:12 1:35	1:36 2:03	2:04 2:38	2:39 3:21	3:22 4 19	4:20 5:48	5:49 8:58	8:59 12:00*
L					0:10 0:26	0:27 0:45	0:46 1:04	1:05 1:25	1:26 1:49	1:50 2:19	2:20 2:53	2.54 3:36	3:37 4:35	4:36 6:02	6:03 9:12	9 13 12:00*
M				0:10 0:25	0:26 0:42	0:43 0:59	1:00 1:18	1:19 1:39	1:40 2:05	2:06 2:34	2:35 3:08	3:09 3:52	3:53 4:49	4:50 6:18	6:19 9:28	9:29 12:00*
N			0:10 0:24	0:25 0:39	0:40 0:54	0:55 1:11	1:12 1:30	1:31 1:53	1:54 2:18	2:19 2:47	2:48 3:22	3:23 4:04	4:05 5:03	5:04 6:32	6.33 9:43	9:44 12:00*
O		0:10 0:23	0:24 0:36	0:37 0:51	0:52 1:07	1:08 1:24	1:25 1:43	1:44 2:04	2:05 2:29	2:30 2:59	3:00 3:33	3.34 4 17	4 18 5:16	5:17 6:44	6:45 9:54	9:55 12:00*
	0:10 0:22	0:23 0:34	0:35 0:48	0:49 1:02	1:03 1:18	1:19 1:36	1:37 1:55	1:56 2:17	2:18 2:42	2:43 3:10	3:11 3:45	3.46 4:29	4:30 5:27	5:28 6:56	6:57 10:05	10:06 12:00*
NEW → GROUP DESIGNATION	**Z**	**O**	**N**	**M**	**L**	**K**	**J**	**I**	**H**	**G**	**F**	**E**	**D**	**C**	**B**	**A**
REPETITIVE DIVE DEPTH																
40	257	241	213	187	161	138	116	101	87	73	61	49	37	25	17	7
50	169	160	142	124	111	99	87	76	66	56	47	38	29	21	13	6
60	122	117	107	97	88	79	70	61	52	44	36	30	24	17	11	5
70	100	96	87	80	72	64	57	50	43	37	31	26	20	15	9	4
80	84	80	73	68	61	54	48	43	38	32	28	23	18	13	8	4
90	73	70	64	58	53	47	43	38	33	29	24	20	16	11	7	3
100	64	62	57	52	48	43	38	34	30	26	22	18	14	10	7	3
110	57	55	51	47	42	38	34	31	27	24	20	16	13	10	6	3
120	52	50	46	43	39	35	32	28	25	21	18	15	12	9	6	3
130	46	44	40	38	35	31	28	25	22	19	16	13	11	8	6	3
140	42	40	38	35	32	29	26	23	20	18	15	12	10	7	5	2
150	40	38	35	32	30	27	24	22	19	17	14	12	9	7	5	2
160	37	36	33	31	28	26	23	20	18	16	13	11	9	6	4	2
170	35	34	31	29	26	24	22	19	17	15	13	10	8	6	4	2
180	32	31	29	27	25	22	20	18	16	14	12	10	8	6	4	2
190	31	30	28	26	24	21	19	17	15	13	11	10	8	6	4	2

RESIDUAL NITROGEN TIMES (MINUTES)

Adapted from US Navy (1985)

No-Decompression Table, and no field requirement for diving should extend beyond them.

Any dive to depths below 35 feet (10 meters) that has a bottom time greater than the no-decompression limit given in this table is a decompression dive and should be conducted in accordance with the Standard Air Table.

NOTE

If field requirements for dives in the depth range 0-21 feet (0 - 6.5 m) exceed the no-decompression limits specified in the No-Decompression Table (Table 14-11), they may be conducted in this range without decompression, regardless of bottom time. Consult the Standard Decompression Schedule Following Normoxic Nitrogen-Oxygen Saturation Exposures (see Section 16) for details.

No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Air Dives (Table 14-11)

Special Instructions

- No-decompression limits column: allowable maximum bottom time that permits surfacing directly at 60 feet/minute (18.3 m/min) with no decompression stops
- For longer bottom times, use the Standard Air Table
- Repetitive group designation table: time periods in each vertical column are the maximum exposures at various depths during which a diver will remain within the group listed at the head of the column
- Repetitive group designation: enter table on exact or next greater depth than exposure and select the exposure time that is exactly the same as or next greater than the actual exposure time. Read the group designation (letter) at the top of the column for the next dive
- Exposure times beyond 5 hours and to depths less than 40 feet (12.2 meters) are beyond the field requirements of this table.

Decompression from most routine air diving operations will be in accordance with the Standard Air Decompression Table (Appendix B). Special instructions for the use of this table are listed below.

14.6.2.2 Standard Air Decompression Table

The Standard Air Decompression Table (Appendix B) combines the Standard Air Table and the Exceptional Exposure Air Table into one table. To delineate clearly the standard and exceptional exposure decompression schedules, the exceptional exposure schedules have been printed in blue.

If the bottom time of a dive is less than the first bottom time listed for its depth, decompression is not required. The diver may ascend directly to the surface at a rate of 60 feet per minute (18.3 m/min). The repetitive group designation for no-decompression dives is given in the No-Decompression Table.

There are no repetitive group designations for exceptional exposure dives. Repetitive dives are not permitted after an exceptional exposure.

Standard Air Decompression Table

Special Instructions

- Rate of ascent between stops is not critical for stops of 50 feet (15.2 meters) or less
- If the dive was particularly cold or strenuous, use the next longer bottom time listed for the schedule used.

14.6.2.3 Residual Nitrogen Timetable for Repetitive Air Dives

If additional dives are conducted within a 12-hour period after any air dive, it is necessary to determine the level of residual nitrogen in the diver's body at the time each additional dive is begun.

During the 12-hour period after an air dive, the quantity of residual nitrogen gradually returns to its normal level. The quantity of residual nitrogen immediately after a dive is designated by the repetitive group letter assigned by either the Standard Air Decompression Table (Appendix B) or the No-Decompression Table (Table 14-11). This designation relates directly to the residual nitrogen level on surfacing. As nitrogen passes out of the tissues and blood, the repetitive group designation changes. The Residual Nitrogen Timetable (Table 14-12) permits this designation to be determined at any time during the surface interval.

Just before beginning a repetitive dive, the residual nitrogen time should be determined by using the Residual Nitrogen Timetable. This time is then added to the actual bottom time to give the bottom time of the equivalent single dive to be used to select the appropriate decompression schedule. Equivalent single dives that require the use of exceptional exposure decompression schedules should be avoided whenever possible.

The upper portion of the Residual Nitrogen Timetable is composed of various intervals between 10 minutes and 12 hours, expressed in hours:minutes (2:21 = 2 hours 21 minutes). Each interval has two limits, a minimum time (top limit) and a maximum time (bottom limit). Residual nitrogen times corresponding to the depth of the repetitive dive are given in the body of the lower portion of the table.

To use the Residual Nitrogen Timetable, the special instructions listed below should be followed for each portion of the Timetable.

NOTE

There is one exception to the Residual Nitrogen Timetable for Repetitive Air Dives: when the repetitive dive is to the same or a greater depth than the previous dive, the residual nitrogen time may be longer than the actual bottom time of the previous dive. In this event, add the actual bottom time of the previous dive to the actual bottom time of the repetitive dive to obtain the equivalent single dive time.

Surface Interval Credit for Air Dives

Special Instructions

- Surface interval time in the schedule is in hours and minutes
- Surface interval must be at least 10 minutes
- Repetitive group designation after surface interval: enter the schedule on the diagonal slope using the group designation from previous dive. Read horizontally until the actual surface interval is equal to or between the interval shown in the schedule. Read the new group designation at the bottom of the column.
- Dives after surface intervals of more than 12 hours are not repetitive dives. Use actual bottom times and the appropriate decompression table to compute the decompression needed for such dives.

Residual Nitrogen Timetable for Repetitive Dives

Special Instructions

- Bottom times listed in this timetable are called residual nitrogen times.
- Residual nitrogen time is the time a diver is to consider that he or she has already spent on the bottom when a repetitive dive to a specific depth is started.
- Residual nitrogen time: enter the timetable vertically with the repetitive group from the surface interval credit table. Read directly the bottom time to be added to the repetitive dive in the depth column for that dive.
- If the surface interval is less than 10 minutes, the residual nitrogen time is the bottom time of the previous dive.

14.6.2.4 Recordkeeping and Table Use

To verify that decompression requirements have been determined accurately, carefully follow the steps outlined in the Repetitive Dive Flowchart (Figure 14-5). A systematic means of recording the steps in the Repetitive Dive Flowchart is the Repetitive Dive Worksheet (Figure 14-6).

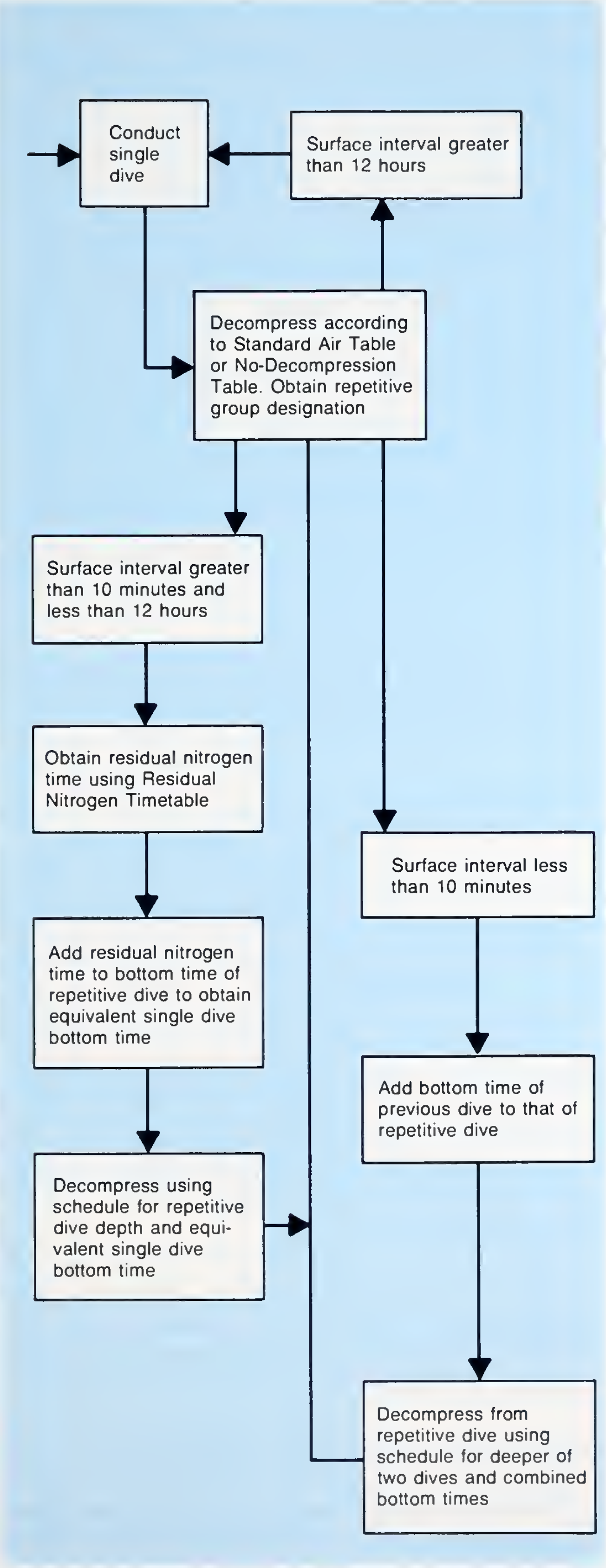
To demonstrate the correct application of the air decompression tables and the proper use of the Repetitive Dive Flowchart and Worksheet, examples of several situations are presented with the appropriate flowchart sequence and worksheet solution. These examples cover most single and repetitive dive situations likely to be encountered during field operations. For correct decompression table and schedule selection, reference should be made to the instructions in Section 14.6.2, any special instructions for the table selected, and instructions for the Residual Nitrogen Timetable.

It is frequently necessary to determine the minimum permissible surface interval for a no-decompression repetitive dive. In this situation, the planned depth and probable duration of the repetitive dive should be evaluated carefully.

To determine the minimum permissible surface interval for a no-decompression repetitive dive, the following sequence of steps should be observed:

- Determine the repetitive group designation from the previous dive.
- Subtract the probable bottom time of the repetitive dive from the applicable no-decompression time limit for the depth of the repetitive dive. The result is the maximum allowable residual nitrogen time after the surface interval.
- Enter the Residual Nitrogen Timetable horizontally with the appropriate depth for the repetitive dive and find the residual nitrogen time that is exactly equal to or less than the maximum allowable residual nitrogen time determined in Step 2.
- Once the appropriate residual nitrogen time is located, move vertically up the column and find the repetitive group designation that corresponds to this residual nitrogen time at the repetitive dive depth.
- From the surface interval credit table portion of the Residual Nitrogen Timetable, enter the table with the repetitive group designation after the previous dive and move horizontally to find the minimum permissible surface interval that corresponds to the necessary new repetitive group designation determined in Step 1.

Figure 14-5
Repetitive Dive
Flowchart



Source: US Navy (1985)

Example:

A diver wishes to make a 35-minute repetitive dive to 60 fsw (18.3 m) after a 12-minute dive to 92 fsw (27.6 m). How long must the surface interval be to make the repetitive dive without decompression?

Solution:

1. The repetitive group designation after the 92/12 dive is given by the 100/15 schedule: E.
2. The no-decompression time limit at 60 fsw (18.3 m) is 60 minutes. The maximum allowable residual nitrogen time is 60 − 35 = 25 minutes.
3. For a 60-fsw repetitive dive, the Residual Nitrogen Timetable indicates a residual nitrogen time of 24 minutes, which is equal to or less than the maximum allowable residual nitrogen time of 25 minutes.
4. This corresponds to a repetitive group designation of D, as found at the head of the column.
5. To drop from one repetitive group designation, e.g., E to D, requires a minimum surface interval of 55 minutes, as shown in Table 14-11.

Many of the national sport diving agencies, as well as other organizations, have developed easy-to-use repetitive dive table formats based on the U.S. Navy tables. Most of these modified formats are pocket-sized, color-coded, and printed on durable plastic cards for field use. They are inexpensive, can aid the diver to calculate repetitive dive times quickly, and fit readily into dive bags or buoyancy compensator pockets. Divers interested in a review of these diving aids should refer to a series of articles published in the January to August 1982 issues of *Skin Diver* magazine.

14.7 SURFACE DECOMPRESSION

Surface decompression is a technique for discharging all or a portion of the diver's decompression obligation in a recompression chamber rather than the water. Using this technique significantly reduces the time a diver must spend in the water, and when oxygen is breathed in the recompression chamber, the diver's total decompression time is reduced even further.

Surface decompression offers many advantages, most of which enhance the diver's safety: (1) shorter exposure to the water prevents chilling; (2) the pressure that can be maintained inside the recompression chamber is constant, unlike the pressure while the diver is decompressing in the water; and (3) the diver can be observed constantly by the chamber operator and monitored intermittently by medical personnel, which means that any signs of decompression sickness can be detected and treated immediately.

Figure 14-6
Repetitive Dive
Worksheet

Example #1—Single No-Decompression Dive
A diver has made a 43-minute dive to 58 fsw. Determine the diver's repetitive group designation.

I. PREVIOUS DIVE:

43 (50) minutes ☒ No-Decompression Table
☐ Standard Air Table
58 (60) feet ☐ Previous Repetitive Drive
H repetitive group designation

II. SURFACE INTERVAL:

______hours______minutes on surface.
Repetitive group from I.______
New repetitive group, from Surface Interval Credit Table______

III. RESIDUAL NITROGEN TIME:

______feet (depth of repetitive dive)
New repetitive group from II.______
Residual nitrogen time, from Residual Nitrogen Timetable______

IV. EQUIVALENT SINGLE DIVE TIME:

______minutes, residual nitrogen time from III.
+ ______minutes, actual bottom time of repetitive dive.
= ______minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

______minutes, equivalent single dive time from IV.
______feet, depth of repetitive dive

Decompression from (check one):
☐ No-Decompression Table ☐ Standard Air Table
☐ Surface Table Using Oxygen
☐ Surface Table Using Air

Decompression Stops:______feet______minutes
______feet______minutes
______feet______minutes
______feet______minutes
______feet______minutes

Schedule used______
Repetitive group______

If an oxygen breathing system is installed in the recompression chamber, surface decompression should be conducted according to the Surface Decompression Table Using Oxygen. If air is the only breathing medium available, the Surface Decompression Table Using Air (see Appendix B) must be used. There is no surface decompression table for use after an exceptional exposure dive. In addition, no repetitive diving tables have been developed for dives after surface decompression.

14.7.1 Surface Decompression Using Oxygen After an Air Dive

The Surface Decompression Table Using Oxygen (Appendix B) is used for surface decompression from an air dive. It is essential that only pure oxygen be breathed during this procedure. If the oxygen supply is interrupted or symptoms of oxygen toxicity are experienced, the decompression may be completed on air. If either of these events occurs, the Surface Decompression Table Using Air should be used (the time spent on oxygen should be disregarded). The notes on the Surface Decompression Table Using Oxygen and the Surface Decompression Table Using Air are self-explanatory and should be followed.

14.7.2 Surface Decompression Using Air After an Air Dive

The Surface Decompression Table Using Air (Appendix B) may be used after an air dive. When surface decompressing on air, the standard air tables should not be used; the Surface Decompression Table Using Air should be used instead.

14.8 OMITTED DECOMPRESSION

Certain emergencies may interrupt or prevent a diver from taking his or her specified decompression stops. Blowup, exhausted air supply, bodily injury, and the like constitute such emergencies. If a diver shows any signs or symptoms of decompression sickness or gas embolism after surfacing, immediate treatment using the appropriate oxygen or air recompression treatment table is essential. Even if the diver shows no signs or ill effects, omitted decompression must be made up in some manner to avoid later difficulty.

Use of Surface Decompression Tables

The Surface Decompression Table Using Oxygen or the Surface Decompression Table Using Air may be used to make up omitted decompression only if the emergency surface interval occurs at such a time that water stops are not required by these tables or, if required, have already been completed.

Surface Decompression Tables Not Applicable

When the conditions that permit the use of the surface decompression tables are not fulfilled, the diver's decompression has been compromised. Special care must be taken in such situations to detect signs of

Figure 14-6
(Continued)

Example #2—Single Decompression Dive

A diver has made a dive to 110 fsw for 25 minutes. Determine the diver's required decompression and repetitive group designation.

I. PREVIOUS DIVE:

25 minutes
☐ No-Decompression Table
☒ Standard Air Table
☐ Previous Repetitive Dive
110 feet
H repetitive group designation

II. SURFACE INTERVAL:

____ hours ____ minutes on surface.
Repetitive group from I. ____
New repetitive group, from Surface Interval Credit Table ____

III. RESIDUAL NITROGEN TIME:

____ feet (depth of repetitive dive)
New repetitive group from II. ____
Residual nitrogen time, from Residual Nitrogen Timetable ____

IV. EQUIVALENT SINGLE DIVE TIME:

____ minutes, residual nitrogen time from III.
+ ____ minutes, actual bottom time of repetitive dive.
= ____ minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

25 minutes, equivalent single dive time from IV.
110 feet, depth of repetitive dive

Decompression from (check one):
☐ No-Decompression Table ☒ Standard Air Table
☐ Surface Table Using Oxygen
☐ Surface Table Using Air

Decompression Stops: 10 feet 3 minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes

Schedule used 110/25
Repetitive group H

Example #3—Repetitive No-Decompression Dive; surface interval greater than 10 minutes but less than 12 hours

A diver has made a 31-minute dive to 55 fsw, takes a 3-hour surface interval, and then makes a 48-fsw dive for 18 minutes. Determine the diver's repetitive group designation.

I. PREVIOUS DIVE:

31 minutes
☒ No-Decompression Table
☐ Standard Air Table
☐ Previous Repetitive Dive
55 feet
G repetitive group designation

II. SURFACE INTERVAL:

3 hours 0 minutes on surface.
Repetitive group from I. G
New repetitive group, from Surface Interval Credit Table C

III. RESIDUAL NITROGEN TIME:

48 feet (depth of repetitive dive)
New repetitive group from II. C
Residual nitrogen time, from Residual Nitrogen Timetable 21

IV. EQUIVALENT SINGLE DIVE TIME:

21 minutes, residual nitrogen time from III.
+ 18 minutes, actual bottom time of repetitive dive.
= 39 minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

39 minutes, equivalent single dive time from IV.
48 feet, depth of repetitive dive

Decompression from (check one):
☒ No-Decompression Table ☐ Standard Air Table
☐ Surface Table Using Air
☐ Surface Table Using Oxygen

Decompression Stops: ____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes

Schedule used 50/40
Repetitive group F

decompression sickness, regardless of what action is initiated. The diver must be returned to pressure as soon as possible. The use of a recompression chamber is strongly preferred to the use of in-water recompression.

When a Recompression Chamber is Available

Even if the diver shows no ill effects from omitted decompression, he or she needs immediate recompression and should be taken to depth for treatment on Recompression Treatment Table 5 or 1A, as appropriate. If the diver shows no ill effects, he or she should be decompressed in accordance with the treatment table. Any decompression sickness developing during or after this procedure should be considered a recurrence.

When No Chamber is Available

When no recompression facility is available, use the following in-water procedure to make up omitted decompression in asymptomatic divers for ascents from depths below 20 feet (6.1 meters):

Figure 14-6
(Continued)

Example #4—Repetitive Decompression Dive; surface interval greater than 10 minutes but less than 12 hours

A diver has made a decompression dive to 80 fsw for 50 minutes, takes a 4-hour, 20-minute surface interval, and then makes a 70-fsw dive for 46 minutes. Determine the diver's decompression and final repetitive group designation.

I. PREVIOUS DIVE:

50 minutes
80 feet
K repetitive group designation

☐ No-Decompression Table
☒ Standard Air Table
☐ Previous Repetitive Dive

II. SURFACE INTERVAL:

4 hours 20 minutes on surface.
Repetitive group from I. K
New repetitive group, from Surface Interval Credit Table C

III. RESIDUAL NITROGEN TIME:

70 feet (depth of repetitive dive)
New repetitive group from II. C
Residual nitrogen time, from Residual Nitrogen Timetable 15

IV. EQUIVALENT SINGLE DIVE TIME:

15 minutes, residual nitrogen time from III.
+ 46 minutes, actual bottom time of repetitive dive.
= 61 minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

61 minutes, equivalent single dive time from IV.
70 feet, depth of repetitive dive

Decompression from (check one):
☐ No Decompression Table ☒ Standard Air Table
☐ Surface Table Using Oxygen
☐ Surface Table Using Air

Decompression Stops: 10 feet 14 minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes

Schedule used 70/70
Repetitive group L

Example #5—Repetitive No-Decompression Dives; surface interval less than 10 minutes

A diver makes a 60-fsw dive for 15 minutes, takes a 5-minute surface interval, and then makes a dive to 50 fsw for 25 minutes. Determine his repetitive group designation.

I. PREVIOUS DIVE:

15 minutes
60 feet
C repetitive group designation

☒ No-Decompression Table
☐ Standard Air Table
☐ Previous Repetitive Dive

II. SURFACE INTERVAL:

____ hours 5 minutes on surface.
Repetitive group from I. N/A
New repetitive group, from Surface Interval Credit Table N/A

III. RESIDUAL NITROGEN TIME:

50 feet (depth of repetitive dive)
New repetitive group from II. N/A
Residual nitrogen time, from Residual Nitrogen Timetable 15

IV. EQUIVALENT SINGLE DIVE TIME:

15 minutes, residual nitrogen time from III.
+ 25 minutes, actual bottom time of repetitive dive.
= 40 minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

40 minutes, equivalent single dive time from IV.
60 feet, depth of repetitive dive

Decompression from (check one):
☒ No-Decompression Table ☐ Standard Air Table
☐ Surface Table Using Oxygen
☐ Surface Table Using Air

Decompression Stops: ____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes

Schedule used 60/40
Repetitive group G

Recompress the diver in the water as soon as possible (preferably less than a 5-min surface interval). Keep the diver at rest, provide a standby diver, and maintain good communication and depth control. Use the following procedure with 1 minute between stops:

- Repeat any stops deeper than 40 feet (12.2 meters)
- At 40 feet (12.2 meters), remain for one-fourth of the 10-foot stop time
- At 30 feet (9 meters), remain for one-third of the 10-foot stop time
- At 20 feet (6.1 meters), remain for one-half of the 10-foot stop time
- At 10 feet (3 meters), remain for 1.5 times the scheduled 10-foot stop time.

14.9 FLYING AFTER DIVING AT SEA LEVEL

The elimination of inert gas from body tissues after an exposure to pressure continues for a period of 24 hours or more after the dive before equilibration with the

Figure 14-6
(Continued)

Example #6—Multiple No-Decompression Repetitive Dives; surface intervals greater than 10 minutes but less than 12 hours

A diver makes a 55-fsw dive for 20 minutes, takes a 2-hour surface interval, makes a second dive to 45 fsw for 56 minutes, takes a surface interval of 1 hour 56 minutes, and then makes a third dive to 70 fsw for 12 minutes. Determine the diver's final repetitive group designation.

I. PREVIOUS DIVE:

20 (20) minutes
55 (60) feet
D repetitive group designation

☒ No-Decompression Table
☐ Standard Air Table
☐ Previous Repetitive Dive

II. SURFACE INTERVAL:

2 hours 0 minutes on surface
Repetitive group from I. D
New repetitive group, from Surface Interval Credit Table C

III. RESIDUAL NITROGEN TIME:

45 feet (depth of repetitive dive)
New repetitive group from II. C
Residual nitrogen time, from Residual Nitrogen Timetable 21

IV. EQUIVALENT SINGLE DIVE TIME:

21 minutes, residual nitrogen time from III.
+ 56 minutes, actual bottom time of repetitive dive.
= 77 minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

77 minutes, equivalent single dive time from IV.
45 feet, depth of repetitive dive

Decompression from (check one):
☒ No-Decompression Table ☐ Standard Air Table
☐ Surface Table Using Oxygen
☐ Surface Table Using Air

Decompression Stops: ____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes

Schedule used 50/80
Repetitive group J

I. PREVIOUS DIVE:

77 minutes
45 feet
J repetitive group designation

☒ No-Decompression Table
☐ Standard Air Table
☐ Previous Repetitive Dive

II. SURFACE INTERVAL:

1 hour 56 minutes on surface.
Repetitive group from I. ____
New repetitive group, from Surface Interval Credit Table F

III. RESIDUAL NITROGEN TIME:

70 feet (depth of repetitive dive)
New repetitive group from II. F
Residual nitrogen time, from Residual Nitrogen Timetable 31

IV. EQUIVALENT SINGLE DIVE TIME:

31 minutes, residual nitrogen time from III.
+ 12 minutes, actual bottom time of repetitive dive.
= 43 minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

43 minutes, equivalent single dive time from IV.
70 feet, depth of repetitive dive

Decompression from (check one):
☒ No-Decompression Table ☐ Standard Air Table
☐ Surface Table Using Oxygen
☐ Surface Table Using Air

Decompression Stops: ____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes
____ feet ____ minutes

Schedule used 70/45
Repetitive group I

ambient partial pressure of nitrogen in the air at the surface is completed. During this period, reducing the ambient pressure further will create a condition identical to the situation that occurs during decompression after a dive. After diving, divers should exercise caution when travelling in mountainous terrain as well as when flying. The cabin atmosphere in a modern, pressurized airplane usually is maintained at an altitude of 8000 feet (2438 meters), and this reduction in pressure may be sufficient to cause inert gas dissolved in a diver's tissues to come out of solution in the form of bubbles, causing decompression sickness. This has occurred, with severe symptoms, in divers who fly after diving. Flying after diving is a recognized hazard that should be avoided. Termination of the flight, which increases the ambient pressure to 1 atmosphere, does not necessarily cause the gas bubbles to decrease sufficiently in size to stop causing symptoms, and recompression treatment may be required to relieve symptoms. Any delay in starting recompression may cause permanent tissue damage and extend treatment time.

Figure 14-6
(Continued)

Example #7—Repetitive No-Decompression Dives; surface interval greater than 10 minutes but less than 12 hours; residual nitrogen time **greater** than actual bottom time of first dive. (This is the **exception** situation.)

A diver has made a 31-minute dive to 80 fsw, takes a 20-minute surface interval, and then makes another dive to 80 fsw for 6 minutes. Determine the diver's repetitive group destination.

I. PREVIOUS DIVE:

31 (35) minutes ☒ No-Decompression Table
☐ Standard Air Table
80 (80) feet ☐ Previous Repetitive Dive
H repetitive group designation

II. SURFACE INTERVAL:

____hours 20 minutes on surface.
Repetitive group from I. H
New repetitive group, from Surface Interval Credit Table H

III. RESIDUAL NITROGEN TIME:

80 feet (depth of repetitive dive)
New repetitive group from II. H
Residual nitrogen time, from Residual Nitrogen Timetable 31*

IV. EQUIVALENT SINGLE DIVE TIME:

31 minutes, residual nitrogen time from III.
\+ 6 minutes, actual bottom time of repetitive dive.
= 37 minutes, equivalent single dive time.

V. DECOMPRESSION FOR REPETITIVE DIVE:

37 minutes, equivalent single dive time from IV.
80 feet, depth of repetitive dive

Decompression from (check one):
☒ No-Decompression Table ☐ Standard Air Table
☐ Surface Table Using Oxygen
☐ Surface Table Using Air

Decompression Stops:____feet______minutes
____feet______minutes
____feet______minutes
Schedule used 80/40 ____feet______minutes
Repetitive group I ____feet______minutes

*In this example, the residual nitrogen time for the second dive from the Residual Nitrogen Timetable would be 38 minutes. This residual nitrogen time exceeds the actual bottom time of the first dive, 31 minutes, and thus the exception rule is called for. In following the steps on the Flowchart and Worksheet, the "residual nitrogen time" is the bottom time of the first dive. If the normal application of the rules were used, the repetitive dive would become a decompression dive requiring decompression on the 80/50 schedule.

Adapted from NOAA (1979)

If it is necessary to fly immediately after a decompression dive, after a series of repetitive dives, or after recompression treatment (as might occur in the case of an injury that requires medical capability beyond that available at the dive site), the diver should be transported at low altitude by helicopter or aircraft or in a plane having a cabin pressure of not more than 800 feet (244 meters) of altitude. The same rules should be followed if a diver experiencing decompression sickness must be transported by air, except that the victim should also breathe pure oxygen until arrival at a recompression chamber.

WARNING

The Following Procedures Do Not Apply to Flying After Saturation Diving (see Section 16.6.2)

Before flying in an aircraft in which the cabin atmosphere is less than 8000 feet (2438 meters) (usually the case in most flights), a diver who has completed any number of dives on air and been decompressed according to the U.S. Navy Standard Air Decompression Table should wait at sea level, breathing air, for the computed surface interval that allows him or her to be classified as a Group D diver, in accordance with the U.S. Navy No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Dives (Table 14-11). This procedure is illustrated by the following example:

0800 Dive to 50 feet (15.2 meters) on air for 60 minutes.
0900 Surface. (The U.S. Navy No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Dives (Table 14-11) indicates that the diver is in repetitive Group H.) Remain at sea level for 5 hours.
1400 U.S. Navy Residual Nitrogen Timetable for Repetitive Air Dives (Table 14-12) indicates that the diver has moved to Group B (dive to 60 feet (18.3 meters) on air for maximum no-decompression time of 49 minutes). This is found by subtracting the residual nitrogen time of 11 minutes for Group B at 60 feet (18.3 meters) (Table 14-12) from the maximum no-decom-

pression time of 60 minutes at 60 feet (18.3 meters) (Table 14-11).

1449 Surface. (Table 14-11 indicates that the diver is in Group J.) Diver must wait 3 hours and 5 minutes to move into Group D.

1754 Diver can now fly at a maximum cabin altitude of 8000 feet (2438 meters).

Before flying, the diver should check with the flight engineer to ascertain the maximum planned cabin altitude and to inform the engineer that divers will be aboard.

To shorten the necessary surface interval before flying, oxygen may be breathed instead of air. Table 14-13 lists, for the various Repetitive Dive Group classifications, the length of oxygen breathing time necessary before flying is allowed.

Table 14-13
Optional Oxygen-Breathing
Times Before Flying After Diving

Repetitive Dive Groups	**Oxygen Time Before Flying**
	(Hr:Min)
Groups M through Z	1:30
Groups H through L	1:00
Groups E through G	0:30
Groups A through D	0:00

Source: NOAA (1979)

SECTION 15
MIXED GAS AND OXYGEN DIVING

MIXED GAS AND OXYGEN DIVING

15

15.0 GENERAL

The term *mixed gas diving* refers to diving operations in which the diver breathes a medium other than air. Mixed gas may be composed of nitrogen and oxygen in proportions other than those found in the atmosphere, or it may be a mixture of other inert gases and oxygen. The breathing gas can also be 100 percent oxygen, which, although technically not a mixed gas, is used under specialized circumstances; the use of oxygen requires knowledge and training similar to that needed for mixed gas diving. During some phases of a mixed gas dive, air may be used as the breathing mixture.

Mixed gas diving operations require detailed planning, specialized and sophisticated equipment, and extensive surface-support personnel and facilities. The very nature of mixed gas operations, and the fact that such dives are often conducted at great depths and for extended periods of time, increases the risks associated with such dives. For these reasons, there is no such thing as a casual mixed gas or oxygen dive.

15.1 MIXED GAS COMPOSITION

Oxygen must be a component of any breathing mixture; the commonly used inert components are nitrogen and helium. Other gases, such as neon and hydrogen, are being studied as replacements for helium. Still others, including argon, sulfur hexafluoride, and carbon tetrafluoride, have been used experimentally to vary the properties of breathing mixtures. The advantages and limitations of these gases are discussed below, in Section 15.1.1.

As is true for any breathing mixture, the quality of the breathing gas is vitally important. (Gas purity standards, including Federal specifications, are covered in Section 14.) In general, few purity problems are associated with gases obtained in cylinders from commercial vendors. The problems that do occur are usually caused by factors such as improper mixing, analysis, labeling, or color coding, contamination resulting from improper handling or a poorly maintained compressor, or solvent residue left in storage containers or hoses. The importance of ensuring that any mixture used for breathing is correct cannot be overemphasized.

The manner in which oxygen and inert gases are combined and used as a breathing mixture depends on both the type of breathing apparatus and the depth of the planned operation. General considerations regarding mixtures based on nitrogen and/or helium are discussed in Sections 15.1.2 and 15.1.3. Mixing techniques are covered in Section 15.5, and the equipment used for mixed gas diving is discussed in Section 15.2.

The physiological effects of each component of a gas mixture are a function both of the partial pressure of that component at the pressure involved and the percentage of that component in the mixture. An understanding of the concept of partial pressure is essential to the safe management of mixed gas diving. The partial pressure (P_p) of a component (Y) in a gas mixture is the product of the total absolute pressure (P_{abs}) of the mixed gas times the fraction constituted by the component

$$P_p = P_{abs} \times Y\%/100.$$

(See Section 2.2.5 for additional information on the physics of diving.)

15.1.1 Limitations of Diluent Gases

The use of nitrogen, the most commonly used diluent, is limited because of its tendency to produce narcosis (see Section 3.2.3.5), in addition to the fact that adding it to an air mixture affects the amount of allowable bottom time for a given decompression obligation. The density of nitrogen is also a detrimental characteristic. When mixtures containing increased nitrogen partial pressures are used with the air decompression tables, the air-equivalent depths must be calculated before diving (see Section 15.1.1).

Helium has not produced narcotic effects on divers at any depth at which it has been used, but its use is limited by its high cost, relative scarcity, high thermal conductivity, and the difficulty of communicating by voice when breathing a helium-oxygen mixture because helium distorts human speech. The communication limitation can be largely eliminated by using a special helium unscrambler that utilizes electronic filtering and special frequency modulation techniques. Helium also has a high diffusivity that allows it to leak through penetrators and into equipment easily, with occasionally disastrous effects.

The thermal conductivity of helium is six times that of nitrogen, which causes heat to be lost from the body very rapidly in a bell or saturation chamber. During a short dive (15 minutes or less) even in very cold water, the amount of heat loss may not be significant, but on a prolonged dive, it can reduce diver efficiency substantially. It is current diving practice on dives to depths greater than 326 fsw (100 msw) to heat helium-oxygen breathing mixtures to reduce the loss of body heat.

Neon is sometimes used as a component of diver's breathing gas, but it is far too expensive to use in the pure state. Neon offers some advantages over helium. Most notably, it has lower thermal conductivity and distorts speech less. A mixture of neon and helium (about 75 percent neon and 25 percent helium) is a by-product of the cryogenic production of oxygen and nitrogen. This mixture is available commercially and is suitable for use as a diluent in diver's breathing gas. Neon does not appear to have narcotic effects, and tests indicate that its decompression requirements are similar to those of helium. However, neon does create more breathing resistance than helium at greater depths.

Hydrogen is not used as often as a diver's breathing gas because of its explosive qualities. By keeping the oxygen concentration in the mixture below the limit of combustion, however, non-explosive hydrogen-oxygen mixtures can be made. Hydrogen causes more speech distortion than helium and its thermal capacity is higher, which causes an even greater rate of body heat loss with hydrogen than with helium. However, the advantage of hydrogen is that it is easier to breathe at great depths because of its low density. The effects of hydrogen on body tissues at high pressure have not yet been fully explored. However, hydrogen or hydrogen-helium mixtures have recently been used on a series of deep dives by French, Swedish, and Norwegian divers. New technology is available that removes the hydrogen in the hydrogen-helium mixture at the beginning of decompression; this decreases the risk of handling hydrogen considerably.

15.1.2 Nitrogen-Oxygen Mixtures

Nitrogen-oxygen breathing gas mixtures are generally used for relatively shallow dives. The most common nitrogen-oxygen mixture is air, which can be used effectively from sea level to depths in the range of 130-150 fsw (40-46 msw). Experience with air as a breathing mixture serves as a starting point for work with other nitrogen-oxygen mixtures. Nitrogen narcosis, covered in detail in Section 3.2.3.5, is the limiting factor in the use of nitrogen-oxygen breathing mixtures. The pressure (depth) at which narcosis symptoms first appear varies considerably among individuals and may vary from day to day in the same person. Experience has shown that individuals may become partially acclimated to higher nitrogen partial pressures after several days of saturation in a hyperbaric nitrogen-oxygen environment; repeated daily exposure to nitrogen-oxygen also may facilitate partial acclimation.

When diving on an air breathing mixture, the first observable symptoms of nitrogen narcosis are likely to occur at a depth of about 100 fsw (31 msw), and they usually worsen rapidly in the depth range between 100 and about 200 fsw (31 and 61 msw). Beyond this depth, the performance of most individuals is significantly compromised.

The fraction of the inert gas (in this case nitrogen) in a breathing mixture is an important factor in determining a diver's decompression requirements. Breathing a nitrogen-oxygen mixture that contains a higher fraction of oxygen than air (which is approximately 79 percent nitrogen and 21 percent oxygen) may reduce the need for decompression stops and may also reduce the narcosis problem. A commonly used breathing gas mixture in NOAA diving is one containing 68 percent nitrogen and 32 percent oxygen. With this enriched air nitrogen-oxygen (nitrox) mixture, the nitrogen partial pressures at 63 and 122 fsw (19 and 37 msw) would be 2.0 and 3.2 ATA, respectively, pressures which are equivalent to those that would occur at depths of 50 and 100 fsw (15 and 31 msw), respectively, if air were being breathed.

Although it has been possible to delay the onset of nitrogen narcosis symptoms and to reduce decompression requirements by using enriched oxygen mixtures, another limitation, oxygen toxicity, must be considered when using such enriched breathing mixtures. Table 15-1 shows, for example, that 180 minutes is the longest recommended exposure to an oxygen partial pressure of 1.3 ATA. In the case of an air dive, this oxygen partial pressure is achieved at 172 fsw (53 msw); however, if an enriched mixture of 68 percent nitrogen-32 percent oxygen is used, this partial pressure is reached at a depth of 102 fsw (31 msw). Thus both nitrogen narcosis and oxygen toxicity must be considered carefully when planning a dive that will use enriched nitrogen-oxygen breathing gas mixtures.

Table 15-1 takes into account the results of new experiments with human subjects, as reported by Butler and Thalmann (1986) and by researchers at the Institute for Environmental Medicine, which are con-

Table 15-1
Oxygen Partial Pressure and Exposure
Time Limits for Nitrogen-Oxygen
Mixed Gas Working Dives

Oxygen Partial Pressure (PO_2) in ATA	Maximum Duration for a Single Exposure (min)	Maximum Duration for a Single Exposure (hr)	Maximum Total Duration for Any 24-Hour Day (min)	Maximum Total Duration for Any 24-Hour Day (hr)
NORMAL EXPOSURE OXYGEN PARTIAL PRESSURE LIMITS				
1.6	45	0.75	150	2.5
1.5	120	2.0	180	3.0
1.4	150	2.5	180	3.0
1.3	180	3.0	210	3.5
1.2	210	3.5	240	4.0
1.1	240	4.0	270	4.5
1.0	300	5.0	300	5.0
0.9	360	6.0	360	6.0
0.8	450	7.5	450	7.5
0.7	570	9.5	570	9.5
0.6	720	12.0	720	12.0
EXCEPTIONAL EXPOSURE LIMITS				
2.0	30	0.5		
1.9	45	0.75		
1.8	60	1.0		
1.7	75	1.25		
1.6	120	2.0		
1.5	150	2.5		
1.4	180	3.0		
1.3	240	4.0		

Normal exposures are those involved in standard diving operations, e.g., dives for research, sampling, inspection and observation, and repair. A series of repetitive dives may be conducted without a normoxic interval between dives if the sum total of the oxygen partial pressure duration limit for all of the dives does not exceed the Maximum Single Exposure Limits.

If one or more dives within a 24-hour period have reached or exceeded the limits for a normal single exposure, the diver must spend a minimum of 2 hours at a normoxic PO_2 before diving again. If one or more dives within a 24-hour period have reached the Maximum Total 24-Hour Day Limits, the diver must spend a minimum of 12 hours at a normoxic PO_2 before diving again.

Exceptional exposures are for use only in lifesaving operations.

Adapted from Butler and Thalmann (1986) and derived from data
in the International Diving and Aerospace Data System,
Institute for Environmental Medicine, University of Pennsylvania
by C. J. Lambertsen and R. E. Peterson

sistent with general industry experience. These results indicate that single exposures somewhat longer than those shown in Table 15-1 can be conducted without episodes of central nervous system (CNS) oxygen toxicity. However, the more conservative exposure times shown in Table 15-1 take operational safety into consideration and are sufficient in duration for anticipated NOAA dives. At the same time, the limits shown in Table 15-1 extend the limits published in the second edition of the *NOAA Diving Manual.*

The values shown in Table 15-1 take pulmonary oxygen toxicity as well as CNS toxicity into consideration. Prolonged and repetitive exposure to high oxygen pressures can cause lung damage, which is initially reversible. In addition, at lower oxygen pressures, pulmonary oxygen toxicity can limit exposures even when CNS oxygen toxicity is not a limiting factor. At the higher PO_2 levels shown in Table 15-1, however, CNS oxygen toxicity is considered the constraint. A simpler way to manage the long-duration aspects of oxygen exposure that takes whole-body toxicity into consideration can be found in the Repex procedures and tables (Hamilton, Kenyon, Peterson et al. (1988a); Hamilton, Kenyon, and Peterson (1988b)).

Recent research reported by Butler and Thalmann (1986) indicates that oxygen tolerance testing does not screen satisfactorily for susceptibility to CNS oxygen convulsions during working dives. Thus, continuation of NOAA's policy, which is not to conduct oxygen tolerance testing, appears appropriate. Butler and Thalmann's experiments did demonstrate a direct correlation between rapid cooling of core temperature and the onset of oxygen toxicity.

Another use for nitrogen-oxygen gas mixtures occurs in shallow saturation and saturation-excursion diving. These dives have traditionally been performed by NOAA divers breathing air during the dive and breathing normoxic nitrox in the habitat. (Saturation diving is discussed further in Section 16.)

15.1.3 Helium-Oxygen Mixtures

For diving to depths greater than 150 to 200 fsw (46 to 61 msw), helium-oxygen mixtures are commonly used; such mixtures often contain some nitrogen as well. The substitution of helium for nitrogen eliminates the nitrogen narcosis problem and makes the gas easier to breathe, but the use of helium is associated with other problems.

One of these is speech distortion, the so-called Donald Duck effect. This distortion has to do with differences in the impedance match between air spaces and the surrounding tissues and the speed of sound in helium. The effect becomes progressively more pronounced with increasing depth. With experience, divers and tenders learn to overcome some of the communication interference imposed by this distorted speech. The problem can be ameliorated further by using pressure-insensitive microphones and one of the commercially available electronic helium speech unscramblers. Such devices are commonly used for mixed gas dives to depths beyond about 300 fsw (92 msw).

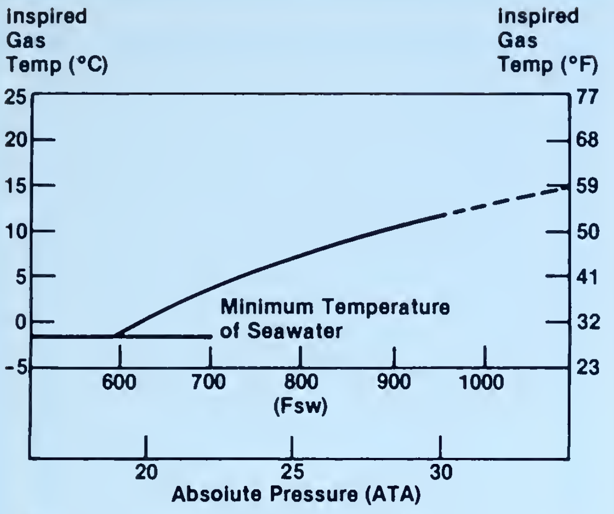
Another problem associated with the use of helium is body heat loss, which is caused in part by the fact that the thermal conductivity of helium is approximately six times that of air. Heat loss occurs both from the skin because of thermal conductivity and from the respiratory tract because of the heat capacity of compressed gas. In deep saturation dives that use helium-oxygen mixtures, there is a significant and continuous insensible heat loss even if the divers are thermally comfortable. The most obvious reflection of this effect is an increased dietary caloric intake, but it also means that special effort needs to be made to ensure that helium-saturated divers are properly rewarmed between dives. Respiratory heat loss increases with depth (with any gas, not just helium) to the point where, at about 800 fsw (246 msw), it is as great as an individual's entire metabolic heat production. For dives of sufficient depth and duration, heating the breathing gas is essential, because without supplemental heating, the temperature of a diver's breathing gas will approach the ambient water temperature, which can be unacceptable if the water is cold. The minimum inspired gas temperatures recommended for a dive of any duration are presented in Figure 15-1.

Divers who are being compressed to deep depths while breathing helium-oxygen mixtures may experience other physiological phenomena. Hyperbaric arthralgia (pain in the joints) may occur during compression and after arrival at the maximum depth. These pains tend to improve with time and can be controlled by compressing slowly. Another problem is the high pressure nervous syndrome (HPNS), which manifests itself in tremors of the hands and jerky movements of the limbs, dizziness, nausea, decreased alertness, and the desire to sleep when not active. Divers have experienced HPNS during heliox and hydrogen-oxygen dives. These symptoms are accompanied by changes in the electrical activity of the brain (as shown by an electroencephalogram). Although the cause of HPNS is not really understood, experience has shown that it can be controlled by using a slow rate of compression, or, for very deep dives, a staged compression profile.

During decompression from a dive using a helium-oxygen breathing gas mixture, the divers may be shifted to an air mixture, both to increase the rate of helium offgassing from the body and, in 'bounce' dives (short, deep dives), to conserve the amount of helium used during the dive. At depths greater than 100 fsw (31 msw), if the body is surrounded by a helium-oxygen mixture (as in a diving bell or chamber) and the diver is breathing a nitrogen-oxygen mixture by mask, gas gradients can develop through the skin, causing a severe itching that is similar to the itching of skin bends and predisposing the diver to vestibular decompression sickness. This phenomenon, in which one inert gas is inhaled while another inert gas surrounds the body, is referred to as isobaric counterdiffusion (see Section 3.2.3.3). Counterdiffusion can be avoided by shifting to air gradually or doing so at a shallow depth and by preventing the divers from breathing air at depths deeper than 100 fsw (31 msw) when their tissues are equilibrated with a helium atmosphere.

Pure oxygen is commonly used for breathing during the later stages of decompression from mixed gas dives. Since oxygen is consumed by the body, it does not contribute to the tissue's gas loading, which must be reduced to provide safe decompression. Oxygen breathing, however, can be used only during the shallower portions of the decompression profile because of the danger of oxygen poisoning (see Sections 3.3 and 20.4.3).

Figure 15-1
Minimum Safe Inspired
Gas Temperature Limits



Fsw	°C	°F	Fsw	°C	°F
600	-1.0	30.1	850	9.4	48.9
650	1.7	35.0	900	10.8	51.5
700	4.0	39.2	950	12.1	53.8
750	6.0	42.9	1000	13.3	55.9
800	7.8	46.1			

Source: NOAA (1979)

15.1.4 Oxygen Concentrations in Breathing Mixtures

The partial pressure of oxygen that is considered normal and to which humans are adapted is 0.21 ATA. A healthy person can maintain the oxygen level of blood at a tolerable level even if the inspired oxygen pressure drops to about 0.16 ATA (16 percent oxygen at atmospheric pressure). Below this level, performance is distinctly impaired; unconsciousness occurs when the level drops acutely below about 0.10 ATA. Levels much below this will cause brain damage or death if maintained for more than brief periods.

Demonstrable pulmonary oxygen toxicity is likely to occur when the inspired oxygen partial pressure exceeds 0.6 ATA for prolonged periods (several days), and acute toxicity may result from much shorter exposures to higher levels. The oxygen partial pressures that can be tolerated for limited periods of time during normal exposures on a regular repetitive basis are shown in Table 15-1. Most people can tolerate partial pressures greater than 2.0 ATA for many minutes while at rest; these levels are used in both routine decompressions and in the treatment of decompression sickness. The partial pressure at which the onset of symptoms of CNS oxygen poisoning occurs varies inversely with activity level and differs significantly among individuals. Symptoms of acute oxygen poisoning that may signal an incipient convulsion are facial twitching, dizziness, nausea, lightheadedness or confusion, euphoria, and dilation of the pupils. At oxygen partial pressures of 1.3 ATA and lower, CNS oxygen toxicity is not likely. Section 20.4.3 provides a further discussion of oxygen poisoning and the appropriate corrective actions. For long-term exposures in a hyperbaric chamber or a habitat, the oxygen partial pressure of the breathing gas should be maintained between 0.3 and 0.4 ATA.

NOTE

The likelihood of CNS oxygen poisoning is directly related to work level.

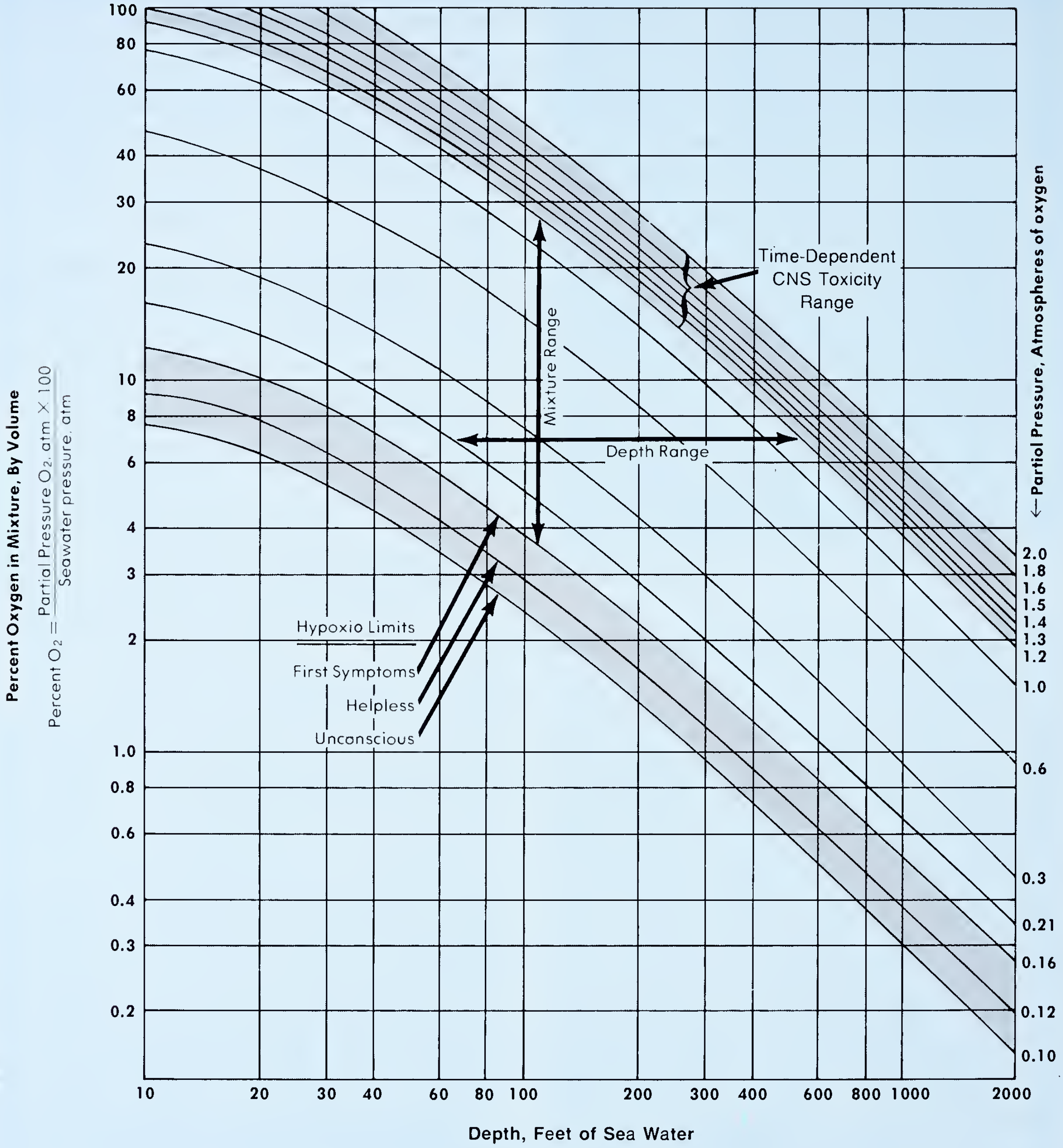
The physiological and toxic boundaries of oxygen partial pressures as a function of depth and percentage of oxygen are shown in Figure 15-2, which shows that, for any fixed depth, it is feasible to breathe a wide range of oxygen mixtures without ill effects. Figure 15-2 and Table 15-1 may be used together to determine the usable depth range and dive duration for a fixed oxygen fraction or percentage. For example, at 10 percent oxygen by volume, a depth range between 21 and 495 fsw (0.16 and 1.6 ATA oxygen) is permissible, provided exposure time at maximum depth does not exceed 45 minutes (Table 15-1).

Certain research investigations and military applications call for the use of a pure oxygen 'rebreather' apparatus. Use of this equipment requires a thorough understanding of the principles and hazards involved; a major problem with these devices is oxygen toxicity. The most recent research results on pure oxygen diving in exercising human volunteers are reported by Butler and Thalmann (1986). Table 15-2 shows depth-time limits for pure oxygen working dives. As noted earlier, exposure times somewhat greater than those shown at the highest pressures in Tables 15-1 and 15-2 are possible without the occurrence of oxygen convulsions; however, NOAA finds that the conservative limits established in Table 15-2 (as well as in Table 15-1) are satisfactory for NOAA diving operations. (Note that the exposure times in Table 15-2 are different from those presented for pure oxygen breathing in the second edition of the *NOAA Diving Manual*.)

15.1.4.1 General Safety Precautions for Oxygen

Oxygen is the most hazardous gas divers handle because it lowers the ignition temperature of flammable substances and greatly accelerates combustion. Hydrocarbons ignite almost spontaneously in the presence of oxygen, and oxygen fires instantly create intense

Figure 15-2
Percentage of Oxygen in Breathing Mixtures
as a Function of Depth and Oxygen Partial Pressure
Relative to Ranges for Hypoxia and CNS Toxicity



A wide range of oxygen mixtures can be used without the diver experiencing ill effects during the dive. For example, near 200 fsw (61 msw), the mixture may contain as little as 3 percent oxygen (0.21 atmosphere partial pressure) in extreme duration exposures. However, at 18 percent oxygen (1.3 atmosphere partial pressure) at the same depth, the diver can remain only for 3 hours (Table 15-1) without deleterious effects.

Adapted from NOAA (1979)

Table 15-2
Depth-Time Limits for
Breathing Pure Oxygen
During Working Dives

Depth (fsw)	Oxygen Pressure (atm)	Maximum Single Dive (min)	Maximum Daily Exposure (min)
5	1.15	180	240
10	1.30	180	210
15	1.45	180	210
20	1.61	150	180
25	1.76	80	150
30	1.91	40	120
35	2.06	20	80

Repetitive dives to the maximum single dive limit must be separated by a 2-hour surface interval. If the maximum daily exposure is reached, these additional dives must be separated by a 12-hour surface interval.

Derived from data in the International Diving and Aerospace Data System, Institute for Environmental Medicine, University of Pennsylvania by C. J. Lambertsen and R. E. Peterson

heat. When materials burn in oxygen, the flame temperatures are higher than they are in air.

Oxygen cylinders should never be completely emptied, but should be maintained with a minimum of 25 psi cylinder pressure to prevent contamination from entering the cylinder. Oxygen systems must be cleaned and kept free of organic contaminants and loose particles; the process used to ensure that oxygen systems are safe to use is called 'cleaning for oxygen service.'

Oxygen of the purity required for diving is generally refined by cryogenic separation from air. In the United States, oxygen is shipped in gas cylinders that are color-coded *green*. The label on the cylinder, also color-coded green, provides exact data as to the grade of oxygen in the cylinder.

15.2 DIVING WITH MIXED GAS AND MIXED GAS DIVING EQUIPMENT

Mixed gas diving can be performed with a variety of equipment, the most common of which can be divided into two general categories: scuba and surface-supplied. Included within the scuba category are the open-circuit, semi-closed-circuit, and closed-circuit systems. The surface-supplied category includes the standard Navy MK 12 heavyweight dress and a variety of lightweight surface-supplied helmets and masks (see Section 5).

Equipment supplied by different manufacturers requires the use of different operating procedures. Therefore, operating manuals for each type of equipment should be obtained from the manufacturer before any of the equipment described below is used.

15.2.1 Scuba

The scuba mode is generally associated with complete autonomy of diver operation. The semi-closed and closed types of scuba systems, however, include variations that utilize a gas umbilical either as a primary or backup source of breathing gas.

15.2.1.1 Open-Circuit Systems

Open-circuit mixed gas systems are identical to common scuba systems in terms of equipment and operation. The only difference is that the gas cylinders are filled with a mixed gas (nitrogen-oxygen or helium-oxygen) rather than air. Since mixed gas is more expensive than air, its use usually is limited to those diving operations where the advantages gained by using a special gas mixture outweigh the cost. These advantages are an increase in allowable diving depth, an increase in possible bottom times for initial or repetitive dives, and (for longer dives) a decrease in decompression time. The most common gases used in open-circuit systems are mixtures of nitrogen-oxygen, helium-oxygen, and helium-nitrogen-oxygen. Although the lack of publicly available decompression tables limits the general use of these mixtures, they are used widely in commercial and scientific diving.

Within a limited range, the air decompression tables can be used to determine a diver's decompression requirements after a nitrogen-oxygen dive. The advantages and limitations of nitrogen-oxygen mixtures other than air are described in Section 15.1.2. These advantages are illustrated further by the no-decompression limits given in Table 15-3 for a 68 percent nitrogen, 32 percent oxygen breathing mixture, a mixture that has been utilized in several NOAA diving operations and is designated NOAA Nitrox-I. The limits shown in Table 15-3 are based on extensive diving experience within NOAA, and the breathing mixtures shown fall in about the mid-range of mixtures used by the U.S. Navy for semi-closed systems. To utilize the standard air decompression tables with an enriched air nitrogen-oxygen breathing mixture, it is first necessary to calculate an equivalent air depth (EAD). This is the depth at which air will have the same nitrogen partial pressure as the enriched mix has at the depth of the dive. The EAD and the bottom time are then used to enter the standard air decompression tables.

EAD is determined as follows:

$$\text{EAD (fsw)} = [(1 - FO_2)(D + 33)/0.79] - 33$$

where FO_2 = fraction of O_2 = percent/100 of O_2 in the gas mixture; D = deepest depth achieved during

Table 15-3

NOAA NITROX-I (68% N_2, 32% O_2) No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Dives

Depth, fsw	No-decompression Limits, min	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
15		60	120	210	300											
20		35	70	110	160	225	350									
25		25	50	75	100	135	180	240	325							
30		20	35	55	75	100	125	160	195	245	315					
40		15	30	45	60	75	95	120	145	170	205	250	310			
45	310	5	15	25	40	50	60	80	100	120	140	160	190	220	270	310
50	200	5	15	25	30	40	50	70	80	100	110	130	150	170	200	
60	100		10	15	25	30	40	50	60	70	80	90	100			
70	60		10	15	20	25	30	40	50	55	60					
80	50		5	10	15	20	30	35	40	45	50					
90	40		5	10	15	20	25	30	35	40						
100	30		5	10	12	15	20	25	30							
110	25		5	7	10	15	20	22	25							
120	25		5	7	10	15	20	22	25							
130	20			5	10	13	15	20								
140	15			5	10	12	15									
150	10			5	8	10										

See Section 15.2.1.1 for an explanation of this table.

Source: NOAA (1979)

the dive (expressed in fsw), and 0.79 is the percentage of nitrogen in air, expressed as a decimal.

Since oxygen partial pressure also may be a limiting factor in nitrogen-oxygen dives, it is calculated as follows:

$$PO_2\,(ATA) = FO_2\,(D + 33)/33$$

where D = deepest depth achieved during dive (expressed in fsw). For NOAA Nitrox-I dives, $FO_2 = 0.32$.

Using these equations, Table 15-4 has been calculated for NOAA Nitrox-I (68 percent N_2, 32 percent O_2) mixtures and gives the EAD associated with actual dive depth, the standard air table that would be used based on the EAD, the oxygen partial pressure at the actual depth of the dive, and, for reference purposes, the maximum allowable normal oxygen exposure time associated with the calculated oxygen partial pressure, as depicted in Table 15-1. As a further aid to users of NOAA Nitrox-I in open-circuit scuba, Appendix D contains nitrox decompression tables that may be entered directly without calculation, using actual depth and bottom time.

WARNING

The Decompression Tables Contained In Appendix D Are Applicable Only to Dives Using NOAA Nitrox-I (68 Percent N_2, 32 Percent O_2) as the Breathing Gas In Open-Circuit Scuba. These Tables Must Not Be Used When Breathing Air or Any Other Nitrogen-Oxygen Mixture

15.2.1.2 Semi-Closed-Circuit Systems

A semi-closed-circuit system is one in which only a portion of the exhaled gas is vented into the sea; the remainder is recirculated within the system and rebreathed. The obvious advantage of this system over the open-circuit system is more efficient utilization of the diver's gas supply, since only a small portion of the inhaled oxygen is used by the body. This in turn means that, for a given gas supply, the diver can spend a longer time under water. Other advantages of semi-closed-circuit systems are:

- Increased depth, because of these systems' ability to use a variety of inert gases and their flexibility to vary the oxygen content;
- Reduction of decompression time and of the likelihood of decompression sickness because the oxygen concentration is increased;
- Possible reduction in the effects of nitrogen narcosis because higher concentrations of oxygen may be used.

The penalty for this increased efficiency is increased complexity of diving equipment and procedures. Because a major portion of the exhaled gas is recirculated, a means must be provided for the removal of exhaled carbon dioxide. Failure to remove the carbon dioxide would result in hypercapnia, discussed in Section 3.1.3.2. The most common method of removing carbon dioxide (CO_2) is by means of a scrubber containing a CO_2 absorbent. As the exhaled gas passes through the packet bed of absorbent, the carbon dioxide is removed. Sodasorb® is the most commonly used absorbent; another

Table 15-4
Equivalent Air Depths (EAD) and Maximum Oxygen Exposure for Open-Circuit Scuba Using a Breathing Mixture of 68% Nitrogen and 32% Oxygen (NOAA Nitrox-I)

Actual Dive Depth, fsw	Equivalent Air Depth, fsw	USN Air Table, fsw	Oxygen Partial Pressure at Actual Diving Depth, ATA	Maximum Oxygen Exposure, min
15	8.3		0.47	--
20	12.6		0.51	720
25	16.9		0.56	720
30	21.2		0.61	570
35	25.5		0.66	570
40	29.8		0.71	450
45	34.1		0.76	450
50	38.4	40	0.80	450
60	47.1	50	0.90	360
70	55.7	60	1.00	300
80	64.3	70	1.10	240
90	72.9	80	1.19	210
100	81.5	90	1.29	180
110	90.1	100	1.39	150
120	98.7	100	1.48	120
130	107.3	110	1.58	45
				*
				*

Maximum oxygen (O_2) exposure = maximum time to be spent at the indicated PO_2 as per NOAA Oxygen Partial Pressure Limits Table for Normal Exposure (Table 15-1). * = Exceptional exposure as per NOAA Oxygen Partial Pressure Limits Table (Table 15-1).

Adapted from NOAA (1979)

material is Baralyme®. The effectiveness of these absorbents is reduced at low temperatures.

NOTE

Semi-closed-circuit scubas are manufactured by several U.S. and European companies. Because of the complexity of this equipment and related safety considerations, operating manuals and training should be obtained from the equipment manufacturer before using it.

Because only a portion of the exhaled gas is vented into the water, the remainder must be stored in a reservoir (breathing bag) until it is used for the next inhalation. Furthermore, the vented gas must be replaced by the addition of a like amount of gas from a gas supply (gas cylinder). Finally, the oxygen deficiency in the exhaled gas caused by the body's metabolic uptake must be corrected for by injecting more oxygen. In most semi-closed systems, the latter two functions, gas addition and oxygen enrichment, are accomplished by a constant mass flow of oxygen-rich gas from a high-pressure gas cylinder into the breathing bag.

Because most semi-closed-circuit systems use a preset flow principle, they are subject to certain operational limitations. The breathing bag oxygen percentage or 'bag level' (average O_2 level in the system) must be predetermined, based on the anticipated work rate of the diver and the maximum allowable oxygen partial pressure at depth. These considerations establish the flow rate setting and oxygen percentage in the supply mixture. The oxygen percentage in the mixture is governed by the maximum partial pressure at depth that may be breathed safely if the recirculation system must be bypassed and the supply gas used for direct breathing. Flow rate setting is based on the percentage of oxygen in the supply mixture and the diver's anticipated work rate or oxygen utilization rate.

The use of a system with preset limits means that these limits cannot be altered during the dive if the underwater situation changes. As an example, depth cannot be increased without the danger of oxygen poisoning, which would occur if the premixed gas was used at a higher pressure. A flow rate set for minimum exertion may be insufficient for a strenuous swim and might also produce hypoxia because of overconsumption of the available oxygen. The depth range over which a semi-closed-circuit system can be employed also is limited by injection gas considerations. A free diver deploying from the surface must have a minimum bag oxygen level of 16 percent at 1.0 ATA to avoid hypoxia. The oxygen concentration in the supply mix and flow rate considerations for the surface condition obviously will govern the maximum depth of the dive because of partial pressure limits. In practice, the maximum depth at which the highest oxygen percentage can be breathed is the depth at which the partial pressure of oxygen equals 1.6 ATA. Common mixtures with this partial pressure are:

- 60 percent oxygen-40 percent nitrogen; maximum depth 55 fsw (17 m).
- 40 percent oxygen-60 percent nitrogen; maximum depth 99 fsw (31 m).
- 32.5 percent oxygen-67.5 percent nitrogen; maximum depth 129 fsw (40 m).

Mixtures that are richer in oxygen decrease decompression requirements but are limited to shallower depths because of concerns for oxygen poisoning.

A number of factors directly affect the duration of the breathing gas supply:

- Flow rate (dependent on work loads and resulting CO_2 production);
- CO_2 absorbent characteristics and canister capacity;
- Changes in depth (duration is decreased because of loss of gas from the breathing bag each time an ascent is made);
- Tank capacity (and the pressure to which it can be filled).

15.2.1.3 Closed-Circuit Systems (Rebreathers)

The closed-circuit (rebreather) system is a further advance in the efficiency of scuba systems that has been achieved at the price of increased complexity. Like the semi-closed-circuit system, the rebreather employs breathing bags and a carbon dioxide scrubber; however, unlike the semi-closed-circuit systems, rebreathers recirculate all of the exhaled gas within the system. Furthermore, the rebreather operates with a constant oxygen partial pressure, regardless of working depth. Oxygen metabolically consumed by the body is replaced from a bottle of 100 percent oxygen.

When using any closed-circuit scuba, the utilization of the available oxygen is nearly 100 percent, because the only gas that is expelled into the surrounding water is the amount that is purged intentionally from the system or vented automatically as the gas expands during ascent. This means that the gas supply will last longer and the quantity of breathing gas that must be carried is smaller. Oxygen consumption will vary, depending on the diver's exertion level (see Table 14-5).

Mixed Gas Rebreathers

Mixed gas rebreathers utilize two distinctly different and separate gas supply cylinders, one of which contains 100 percent oxygen and the other a diluent gas. The diluent gas may be air, nitrogen/oxygen, or helium/oxygen. The choice of nitrogen or helium in the diluent depends on the depth of the dive. The inclusion of oxygen in the diluent provides a source of oxygen in the event of failure of the oxygen control system. Diluent gas is added automatically and breathing gas is vented automatically from the breathing bags to keep the pressure in the breathing circuit equal to the pressure of the surrounding water. Oxygen is added automatically to the breathing circuit to maintain a fixed, preselected oxygen partial pressure in the circuit. Manual bypass systems are included for both oxygen and diluent gases.

The added complexity of mixed gas rebreathers (see Figure 15-3) is a result of the oxygen control system. Sensors that measure oxygen partial pressure are installed in the breathing circuit. More than one sensor is used to provide redundancy in the event of sensor failure during a dive. The output of these sensors is fed to a display that is monitored by the diver and that reads out the oxygen partial pressure in the breathing circuit. Sensor output also is fed to an electronic control circuit that compares the sensor output to a preset value that represents the desired oxygen partial pressure. If the sensor output indicates that the oxygen partial pressure in the breathing circuit is within the preset limits, no oxygen is added to the circuit. However, should the oxygen partial pressure be less than the preset limit, power is provided to pulse open a solenoid that permits a fixed amount of oxygen to flow from the oxygen bottle into the breathing circuit. Power to operate the oxygen control system is provided by batteries that must either be recharged or replaced after each dive. The rebreather's operating duration is relatively independent of depth and is usually limited by the capacity of the carbon dioxide scrubber.

Oxygen Rebreathers

An oxygen rebreather is a special type of rebreather requiring no diluent gas, which means that the diver breathes 100 percent oxygen. The oxygen rebreather utilizes breathing bags and a carbon dioxide scrubber, as in the case of mixed-gas rebreathers; however, since

Table 15-5
Air Purity Standards

Component	Purity
—Oxygen concentration	20-22% by volume
—Carbon dioxide	1000 ppm maximum
—Carbon monoxide	20 ppm maximum
—Total hydrocarbons other than methane	25 ppm maximum
—Particulates and oil mist	5 mg/m^3 maximum
—Odor and taste	Not objectionable

Measured at standard temperature and pressure.

Source: US Navy (1988)

the diver breathes 100 percent oxygen, there is no requirement for an oxygen control system or batteries. Most units have a mouthpiece breathing valve assembly, breathing hoses, inhalation and exhalation breathing bags, a CO_2 absorption canister, an oxygen supply cylinder, and an adjustable gas-flow regulating assembly (Figure 15-4). This simplification in the equipment, however, does impose severe restrictions on the manner in which the oxygen rebreather may be used. The most significant of these restrictions is the limitation on operating depth.

When using a closed-circuit oxygen rebreather, it is necessary to purge both the apparatus and the lungs with oxygen before entering the water to eliminate nitrogen and air from the breathing system. If the excess air is not eliminated from the breathing bags and lungs before the initiation of oxygen breathing, sufficient nitrogen may remain in the system to provide a breathable volume of a hypoxic gas mixture. During a prolonged dive, the nitrogen eliminated from the body can cause a measurable increase of nitrogen in the breathing medium. The danger of excess nitrogen in a closed-circuit system is that hypoxia (see Section 3.1.3.1) may occur if the volume of nitrogen is enough to dilute or replace the oxygen. Unconsciousness or death may result from hypoxia (see Figure 15-2).

WARNING

Divers May Not Be Able to Sense the Onset of Hypoxia

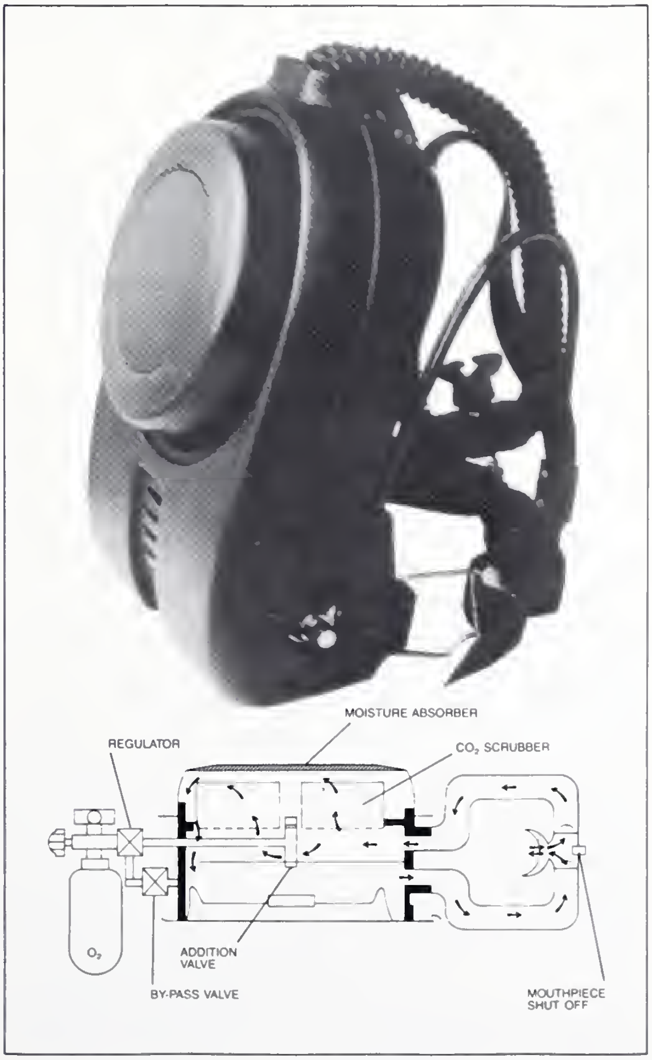
Advantages and Limitations

The advantages of closed-circuit oxygen scuba include freedom from bubbles, almost completely silent operation, and maximum utilization of the breathing medium carried by the diver. A small oxygen supply lasts a long time, and the duration of the supply is not decreased by depth. Divers are not subject to decompression sickness or nitrogen narcosis while using closed-circuit

Figure 15-3
Closed-Circuit
Mixed-Gas
Scuba (Rebreather)

Courtesy Biomarine, Inc.

Figure 15-4
Closed-Circuit Oxygen
Scuba (Rebreather)



Courtesy Biomarine, Inc.

oxygen scuba because there is no inert gas in their breathing gas.

The major limitations of oxygen rebreathers are related to the toxic effects of oxygen on the body, which sharply limit the depths at which rebreathers can be used safely. The oxygen system must be thoroughly purged at the beginning of each dive, after 1 hour of submergence, and again immediately before ascent. An excess of carbon dioxide can build up in the system as a result of absorbent exhaustion, wetting of absorbent, improper canister filling, or over-breathing of the system.

Because of the chance of oxygen poisoning, NOAA rarely uses oxygen rebreathers at depths in excess of 25 fsw (8 msw) (Table 15-2). Dives deeper than this depth will result in a much shorter allowable bottom time; for example, the maximum permissible dive using this apparatus for a period of 20 minutes is 35 fsw (11 msw, Table 15-2). The use of rebreathers beyond these limits can result in serious or fatal accidents involving oxygen convulsions. The amount of training required and the extensive maintenance requirements further restrict the use of this equipment.

NOTE

Oxygen rebreathers are manufactured by several U.S. and European companies. Operating manuals and training must be obtained from the manufacturer before attempting to use any rebreather.

15.2.2 Surface-Supplied Mixed Gas Equipment

Surface-supplied mixed gas diving includes those forms of diving in which a breathing mixture other than air is supplied to the diver through a hose from the surface. Either nitrogen-oxygen or helium-oxygen gas mixtures may be employed, depending on the depth of the dive. In addition to the U.S. Navy MK 12 surface-supported diving system, there are a wide variety of masks and helmets manufactured worldwide that may be employed (see Section 5). Most military surface-supplied equipment utilizes a constant flow of breathing gas through the mask or helmet. Although this results in a very high gas usage rate, equipment of this type is simple to use. To reduce gas consumption, some surface-supplied equipment incorporates a recirculation feature that permits a portion of the gas leaving the helmet to be recirculated through a carbon dioxide scrubber and back through the mask. The most popular surface-supplied equipment in commercial use employs a demand mechanism similar to that of scuba (except that it is supplied by an umbilical). Because of the complexity of the equipment required on the surface, including large supplies of gas, various quantities of different gas mixtures, compressors, special decompression tables, and so forth, surface-supplied diving generally is limited to military, commercial, or scientific applications.

15.3 BREATHING GAS PURITY

Whatever the breathing gas or gases used, it is essential that the necessary standards of purity be met. Standards are set by the Federal government and by private organizations.

15.3.1 Compressed Air Purity

There are several specifications for the purity of breathing air. The requirements most applicable to divers' breathing air are discussed in:

- *U.S. Navy Diving Manual* (1988)
- Occupational Safety and Health Administration, Standard for Commercial Diving Operations (29 CFR 1910, Subpart T)
- Compressed Gas Association Grade F standard
- American National Standards Institute, Z86.1 standard.

The most commonly used air standards for safe diving practice are summarized and shown in Table 15-5.

15.3.2 Diluent Gas Purity

Mixed gases are used with mixed gas scuba or with equipment using helmets designed specifically for mixed gas. Various grades of the different gases are produced for different uses.

Helium is produced in several quality verification levels (QVL); QVLG is approximately 99.999 percent pure, is free of oil and moisture, and is suitable for use in diving. Several private manufacturers and the Federal government produce helium.

Nitrogen, oxygen, and neon are produced by the cryogenic fractioning of air. Hydrogen is produced as a by-product of a number of chemical processes or by the electrolysis of water.

Nitrogen purity is defined in Federal Specification BB-N-411C. This specification describes three grades of Type I (gaseous), Class 1 (oil free) nitrogen:

- Grade A is 99.95 percent pure, low moisture content, no solids;
- Grade B is 99.5 percent pure, low moisture content; and
- Grade C is 99.5 percent pure, no moisture content specified (US Navy 1987).

Nitrogen of Class 1 in Grades A, B, or C may be used for diving operations if the trace contaminants in the gas, which may not constitute more than 0.5 percent by volume, consist only of oxygen and carbon dioxide. A high percentage of CO_2 contamination in Grades B or C nitrogen may preclude its use as breathing gas. The label on the cylinder may provide data about class and grade.

The individual gases used in preparing various breathing mixtures are available in a highly pure state. Any trace contaminants are usually the result of cleaning agents used to prepare the gas containers. (For additional information, see the most recent Compressed Gas Association *Handbook of Compressed Gases.*)

15.3.3 Oxygen Purity

The purity standards for oxygen are detailed in Military Specification MIL-0-27210 (US Navy 1988). This specification categorizes oxygen in the following three grades:

- Grade A Aviator's oxygen
- Grade B Industrial, medical oxygen
- Grade C Technical oxygen.

Grades A and B differ in moisture content. Grade A, used by aviators, must be extremely dry to prevent freezing at the low temperatures associated with high altitudes. Grade B is allowed to contain a maximum of 5 ml of free water per cylinder. Grades A and B oxygen are suitable for use in a breathing medium for divers. Both Grades A and B are required to be 99.5 percent pure oxygen and must pass tests for acidity and alkalinity, carbon dioxide, carbon monoxide, halogens, and other oxidizing substances, as specified in the current edition of the *U.S. Pharmacopoeia.* Grade C, technical oxygen, is safe to breathe, but it may have an objectionable odor and, for that reason, should not be used in diving.

15.4 BREATHING GAS ANALYSIS

The type and concentration of the constituents of breathing gas are vitally important because adverse physiological reactions can occur whenever exposure durations and concentrations of various components in the breathing atmosphere vary from prescribed limits. The quality of the breathing gas is important in both air and mixed gas diving. Because the basic composition of the gas is fixed in air diving, primary attention is directed toward the identification of impurities (carbon monoxide, hydrocarbons) that may be present in the air supply and the effects of inadequate ventilation (carbon dioxide).

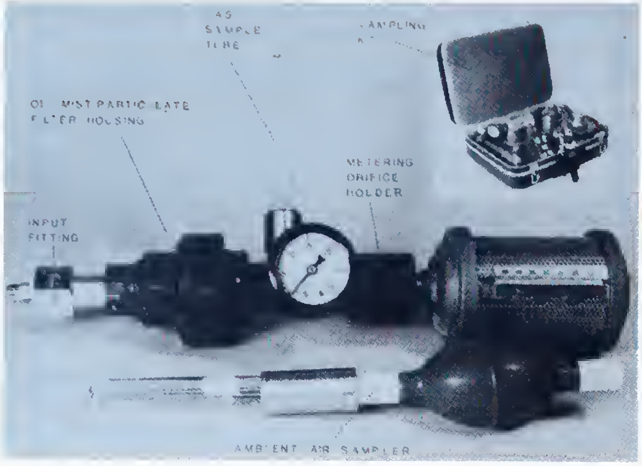
The use of gas analysis is essential in mixed gas diving. Because both hypoxia (oxygen partial pressures below the normal range) and oxygen poisoning are real hazards in mixed gas diving, it is essential that the oxygen content of the gas supply be known before a dive. Oxygen analysis is the most common but not the only type of analytical measurement performed in mixed gas diving. When selecting an instrument to analyze one or more constituents of a gaseous atmosphere, two instrument characteristics are particularly important: accuracy and response time. Both accuracy and sensitivity within the range of the expected concentration must be adequate to determine the true value of the constituent being studied; this can be a problem when samples must be taken at elevated pressure. It is also important that the response time of the instrument be adequate for the situation. Other factors that may be important in the selection of analytical instruments are accuracy, reliability, sampling range, portability, and cost.

Instruments for testing the composition and purity of gases fall into two categories: those for laboratory use and those for field use. Laboratory instruments are complex and highly accurate and include the mass spectrometer, the gas chromatograph, and other chemical analysis devices. These instruments generally are not available at dive sites because they require specialists trained in their use, operation, calibration, and interpretation of the data and are expensive.

Some private and state agency health laboratories provide air analysis services. Several private laboratories provide diver air analysis services and will supply diving firms or organizations with air sampling kits designed to meet the requirements specific to the air supply system being used (Figure 15-5). Using this equipment and the directions supplied with such kits, air samples can be collected from the compressor, particulate samples for oil mist and solid particles can be collected from the compressor's filter system, and samples of the ambient air can be obtained to provide background levels of contamination. The kit and samples are returned to the laboratory for immediate analysis. Using modern gas chromatography equipment and other appropriate techniques, the samples are analyzed for carbon monoxide, carbon dioxide, methane, total gaseous hydrocarbons, oxygen, nitrogen, oil mist, and other particulates. U.S. Navy standards are generally used as an air purity guideline.

Instruments also are available for field use that provide sufficiently accurate data to determine whether a gas

Figure 15-5
Air Analysis Kit
for On-Site Use



Courtesy Texas Research Institute

is safe to use as a breathing medium. Field instruments that operate on the colorimetric principle are available to measure a large number of gases (e.g., oxygen, hydrocarbons, carbon monoxide, carbon dioxide, etc.). These devices come with several different tubes, each specific for a particular gas or group of gases. When the material in the tube comes into contact with a specific gas, it changes color. Portable instrumentation is used to determine the percentage of oxygen in the gas, the gross percentage of carbon dioxide, and the amount of carbon monoxide present; however, field instruments are not capable of precise analysis of the total gas composition. A brief description of portable gas analysis equipment follows.

Oxygen analyzers. Several portable oxygen analyzers are available for measuring the percentage of oxygen in a gas. Calibration of these instruments is important, and calibration instructions are usually included with the equipment. Oxygen content can be determined by using a fuel cell or paramagnetic analyzer, a gas chromatograph, a standard volumetric gas analyzer, an electrometric analyzer, a thermal conductivity analyzer, or color-indicating tubes.

Carbon dioxide analyzers. Analysis conducted in the field can detect only gross amounts of carbon dioxide (CO_2) in a breathing medium. Field-use CO_2 analyzers are capable of detecting CO_2 in quantities of less than 1 percent. Any diver's gas that contains a gross amount of CO_2 is not safe to use. Carbon dioxide content can be determined by using a gas chromatograph, titrimetric analysis, a standard volumetric gas analyzer, an infrared analyzer, or color-indicating tubes.

Carbon monoxide analyzers. Equipment also is available for the laboratory or on-site determination of carbon monoxide in ambient air. Field equipment works either on the potentiometric or colorimetric (Figure 15-6) principle. Potentiometric analyzers are generally more costly than colorimetric devices, and color-indicating analyzers are therefore used more frequently.

It is commonly assumed that unpolluted air compressed in a well-maintained compressor designed for compressing breathing gas will meet oxygen and carbon dioxide requirements without testing. However, a simple test for water, oil, or particulate matter in the gas can be performed. The gas cylinder is inverted for at least 5 minutes in the valve-down position. The valve is then opened slightly, and air is allowed to flow into a clean glass container. If the gas is contaminated, oil, water, or particulate matter can be observed on the glass. Laboratory methods for testing for water in breathing gas include the electrolyte monitor, the piezoelectric hydrometer, the standard dew point apparatus, or an electrical conductivity test. Ultraviolet spectroscopy is used to test for oil contamination.

The total hydrocarbon content in air can be determined in a laboratory using a total hydrocarbon analyzer. For further information on gas analysis equipment, see the *US Navy Diving Manual* (1988).

Compressed air sources should be tested at least semi-annually. Compressed air from an untested source should not be used except in unusual or emergency conditions; under these conditions, it is recommended that the diver breathe the air for a few minutes at the surface before diving.

15.5 GAS MIXING

Two or more pure gases or gas mixtures may be combined by a variety of techniques to form a final mixture of predetermined composition. The techniques for mixing gases, in the order of their frequency of use, are:

(1) Continuous-flow mixing, in which a precalibrated mixing system proportions the amount of each gas in a mixture as it is delivered to a common mixing chamber.

(2) Mixing by partial pressure, which is based on the fact that the proportion by volume of each gas in a mixture is directly related to its partial pressure (to the extent that the gases behave as 'ideal' gases).

Aboard ship, where space is limited and motion might affect the accuracy of precision scales, gases normally

Figure 15-6
Direct-Reading Colorimetric
Air Sampler

Courtesy Draegerwerk AG

are mixed by partial pressure or by continuous-flow mixing systems.

15.5.1 Continuous-Flow Mixing

Continuous-flow gas mixing systems perform a series of functions that ensure extremely accurate mixtures. Constituent gases are regulated to the same pressure and temperature before they are metered through precision micrometering valves. The valve settings are precalibrated and displayed on curves that are provided with every system and that relate final mixture percentages to valve settings. After mixing, the mixture is analyzed on-line to provide a continuous history of the oxygen percentage. Many systems have feedback controls that automatically adjust the valve settings when the oxygen percentage of the mixture varies from preset tolerance limits. The final mixture may be supplied directly to a diver or chamber or be compressed into storage tanks for later use.

15.5.2 Mixing by Partial Pressure

This method frequently is used in filling cylinders aboard ship or in the field. It employs high-pressure gas sources from which gases are mixed according to the final partial pressure desired. The basic principles behind this method are the ideal gas laws, such as Dalton's Law of Partial Pressures, which states that the total pressure of a mixture is equal to the sum of the partial pressures of all the gases in the mixture.

Two methods are available to calculate the partial pressure of a gas in a mixture: the ideal-gas method and the real-gas method. The ideal-gas method assumes that pressure is directly proportional to the temperature and inversely proportional to the volume of a contained gas. The real-gas method additionally accounts for the fact that certain gases will compress more or less than other gases.

Compressibility is a physical property of every gas: oxygen compresses more than helium. Therefore, if two cylinders with the same internal volume are filled to the same pressure, one with oxygen and the other with helium, the oxygen cylinder will hold more cubic feet of gas than the helium cylinder. As pressure is increased or as temperature is decreased, the difference in the amount of gas in each cylinder will increase. The same phenomenon occurs when any two gases are mixed together in one cylinder. In the case of oxygen and helium, if an empty cylinder is filled to 1000 psia with oxygen and then topped off to 2000 psia with helium, the resulting mixture will contain more oxygen than helium.

An awareness of the differences in the compressibility of various gases usually is sufficient to avoid many of the problems encountered when mixing gases. When using ideal-gas procedures, knowledgeable divers add less oxygen than is called for, analyze the resulting mixture, and compensate as necessary. As an alternative when mixing certain specific mixtures, the *US Navy Diving Gas Manual* (1971) may be consulted for procedures to calculate the partial pressures of each gas in the final mixture. These procedures take into account the compressibility of the gases being mixed. Regardless of the basis of the calculations used to determine the final partial pressures of the constituent gases, the mixture always must be analyzed for oxygen content before use.

SECTION 16
SATURATION DIVING

SATURATION DIVING 16

16.0 GENERAL

As interest in the oceans and man's ability to work there increase, techniques and facilities are needed that will enable the scientist or working diver to remain at depth for longer periods of time. An approach that has proved useful in underwater scientific research is nitrogen-oxygen and air saturation-excursion diving from habitats positioned on the seabed. Habitat-based diving is relatively new, and techniques for this type of diving are still developing. To improve the safety and effectiveness of nitrogen-oxygen saturation techniques further, organizations using these procedures are requested to report their experience to the NOAA Diving Program.

Saturation is the term used to describe the state that occurs when a diver's tissues have absorbed all the nitrogen or other inert gas they can hold at any given depth. Once tissue saturation has occurred, the length of the decompression that will be required at the end of the dive will not increase with additional time spent at that depth.

Under saturation conditions, the diver works out of a pressure facility whose atmosphere is maintained at approximately the same pressure as that of the surrounding water or, in a chamber, of the working depth. The saturation facility may be an ocean floor installation, a pressurized chamber on board a surface vessel, or a diver lockout submersible.

The term *habitat* usually is applied to a pressure- or ambient-pressure vessel that is placed on the floor of the ocean and that provides basic life support, comfort, and a base of operation for the diver and the necessary support equipment. Habitats are maintained at a pressure that is equivalent to the pressure of the seawater at the habitat's entrance hatch. (See Section 17 for more information on habitats.)

A **surface-based saturation diving system** consists of a deck decompression chamber (DDC) that is located on a surface support platform and a pressurized diving bell that the saturation diver uses to commute to and from the underwater worksite. The DDC, which provides facilities for the life support and comfort of the saturated diver, may be maintained at a pressure that is close to that of the working depth. The personnel transfer capsule (PTC) (which can be either a diving bell or a lockout submersible) also is maintained at a pressure close to that of the working depth. During transfer from one chamber to another, the PTC is mated to the DDC to enable the diver to remain at pressure at all times.

A diver lockout submersible is a vehicle designed with at least two separate compartments; these compartments enable the divers to enter and exit the water while submerged. Regardless of the system used, the saturation diver undergoes decompression only on completion of the total dive sequence rather than at the end of each dive (unless an excursion dive requiring decompression has been made).

Saturation diving is an essential technique for the scientist who needs to spend long periods on the bottom and for the working diver who wishes to extend the working portion of the dive. Since 1958, when Captain George Bond, USN, conducted the laboratory experiments that led to the development of saturation diving (Bond 1964), saturation diving programs have been carried out by a variety of organizations from many nations, using both land-based hyperbaric chambers (simulated dives) and habitats or bells in the open sea. The saturation depths employed in these programs have ranged from 26 to 2250 fsw (8 to 686 m). Although the military and commercial diving industries have devoted substantial effort to developing practical saturation diving techniques involving helium-oxygen gas mixtures for use at depths to 1000 fsw (307 m) and deeper, NOAA has concentrated on saturation diving in shallower waters (40 to 300 fsw; 12 to 92 m) utilizing more readily available and less costly nitrogen-based gases, particularly air. This section discusses various aspects of saturation diving and provides, for historical interest, summaries of some air and nitrogen-oxygen exposures (Table 16-1).

16.1 PRINCIPLES OF SATURATION DIVING

The tissues of a diver's body absorb inert gases as a function of the depth and duration of the dive, the type of breathing mixture used, the characteristics of the individual diver's tissues, and factors affecting the diver's condition at the time of the dive, such as temperature and work rate. In long-duration dives, the diver's body tissues become saturated with the inert gases in the breathing mixture at the partial pressure of each inert gas component in the mixture.

Table 16-1
Summary of Air and Nitrogen-Oxygen Saturation Exposures

Date	Project	Data Source	Breathing Gas or PO_2	Depth, fsw	Duration, Days	Team Size/ Total No. Participants	Comments Concerning Period of Saturation Exposure
1962	Conshelf I	Chouteau 1969	air	35	7	2	Some adaptive responses
1962	Conshelf II	Chouteau 1969	air	35	30	5	
1965	Glaucus	Miller and Koblick 1984	air	35	7	2	
1966	Bubble	Miller and Koblick 1984	air	31	1/2	14-21	No decompression sickness on direct ascent to surface
				31	1	4-6	Decompression sickness on direct ascent to surface
1966-67	Ikhtiandr	Miller and Koblick 1984	air air	39.4 40	1-2 7	3 12	
1967	USN	Larsen and Mazzone 1967	air	35	1.25	13	
1967	Meduza-I	Miller and Koblick 1984	air	78.7	6	3	
1967	Meduza-II	Miller and Koblick 1984	air	85	8	3	
1967-68	Hebros	Miller and Koblick 1984	air	23	7	5	
1968	Malter-I	Miller and Koblick 1984	air	26	2	2	
1968-74	Chernomor	Miller and Koblick 1984	0.40	45.9	2.5-6.5	28	Decending excursions to 295 fsw
			0.36	82	3.5-16.5	13	
			0.425/0.30	49.5	53	5	Symptoms of pulmonary oxygen toxicity during excursions until habitat PO_2 reduced for final 12 days in saturation
			0.23-0.27	65.6	16	3	
				98.4	12	3	
			0.20-0.22	131.2	16+	3	
			0.20-0.33	101.7	23	5	
			0.20-0.33	101.7	27-28	4-5	

Table 16-1
(Continued)

Date	Project	Data Source	Breathing Gas or PO_2	Depth, fsw	Duration, Days	Team Size/ Total No. Participants	Comments Concerning Period of Saturation Exposure
1968-74	Chernomor	Miller and Koblick 1984	0.23-0.34 0.24-0.34	60.7 65.6	15.5 17.5	5 5	
1969	TEKTITE I	Pauli and Cole 1970	0.21	42	60	4	
1969	Helgoland	Miller and Koblick 1984	0.25	75.4	6-12	8	
1970	Predictive Studies II	Lambertsen and Wright 1973	0.21	100	14	6	No serious toxic, narcotic, or physiological effects; some adaptive responses
1970	TEKTITE II	Beckman and Smith 1972	0.21	50	5-20	56	
1970	LS-I	Miller and Koblick 1984	air	33	32	3	
1970	Shelf-I	Miller and Koblick 1984	air	65.6	4.5-6	6	
1970	EDALHAB I	Miller 1976	air	26	2	4	
1971	EDALHAB II	Miller 1976	air	43	4	2	
1971	Tonofond	Miller 1976	0.33	49	3-10	14	
			0.33	65	3-10	12	
			0.33	81	3-10	12	
1971	Hydrolab	Miller and Koblick 1984	air	50	2-8	24	
1972	FLARE	Miller 1976	air	42-45	5	25	
1972	Pre-SHAD I	Miller 1976	air	50	2	2	Intolerance to oxygen during treatment of decompression sickness
1972	NOAA-Ops I	Hamilton et al. 1973	0.21	30	7	3	
			0.21	90	7	3	
1972	NOAA-Ops II	Hamilton et al. 1973	0.21	60	7	2	
			0.21	120	7	3	One diver sick (relationship to pressure exposure uncertain); no gross impairment due to narcosis

Table 16-1
(Continued)

Date	Project	Data Source	Breathing Gas or PO_2	Depth, fsw	Duration, Days	Team Size/ Total No. Participants	Comments Concerning Period of Saturation Exposure
1972-74	La Chalupa	Miller and Koblick 1984	0.23, 0.25	50, 60	15	36	
1972-75	Hydrolab	Miller 1976	air	42, 60	2-14	317	
1973-75	Lora	Miller 1976	air	26	1	7	
1973	PRUNE I	Miller 1976	0.16-0.39	95	14	4	
1973	SHAD I	Miller 1976	air	50	29	2	12.5% decrease in red blood cell mass
1973	Helgoland	Miller and Koblick 1984	0.25	75	5	3	
1973-75	Hydrolab	Miller and Koblick 1984	air	42, 45, 60	2-14	164	
1974	SHAD II	Miller 1976	air	60	27	2	19.3% decrease in red blood cell mass
1974	SHAD III	Miller 1976	air	50	7	3	Intolerance to oxygen during treatment of decompression sickness
1974	PRUNE II	Miller 1976	0.17-0.42	106	11	4	
1975	SCORE I	Miller 1976	air	60	5	8	Significant reduction in vital capacity in some subjects, decreased O_2 tolerance in air excursion, significant decrease in red blood cell mass
1975	SCORE II	Miller 1976	air	60	5	16	13.3% decrease in red blood cell mass
1975	Helgoland		0.36-0.50	112	3-16	14	Narcosis in some individuals
1975	NISAT I	Hamilton et al. 1982	0.21-0.3	198	7 + 7 for decompression	3	Vertigo and nausea in two divers during initial hours of dive; PO_2 raised to 0.3 ATA
1975	NISAT II	Hamilton et al. 1982	0.3	66	8	3	Isobaric switch from nitrogen to helium on dive day 3; mild pruritis in two divers. Decompression on helium

Table 16-1
(Continued)

Date	Project	Data Source	Breathing Gas or PO_2	Depth, fsw	Duration, Days	Team Size/ Total No. Participants	Comments Concerning Period of Saturation Exposure
1976	NISAT III	Hamilton et al. 1982	0.3	99	8	3	Isobaric switch from nitrogen to helium on day 3; all divers experienced severe pruritis and urticaria; after change of inert gases, one diver developed isobaric decompression sickness that required therapy consisting of increasing depth to 129 fsw and breathing increased oxygen. Decompression on helium
1976	AIRSAT I	Eckenhoff and Vann 1985	air	60	8	11	Three dives, daily 8-hour no-decompression excursions to 100 fsw. Significant vital capacity reduction in one diver
1977	Neritica	Miller and Koblick 1984	air	29	0.5-17	82	
1977-79	AIRSAT II	Eckenhoff and Vann 1985	air	60	10	12	Three dives, daily 2-hour excursions to 150 fsw with 160 min decompression back to storage depth
1978-85	Hydrolab	NOAA	air	47	7	357	
1979	Commercial Welder Training	Peterson et al. 1980	air He-15% O_2 air air	45 79 79 65	4 8-10 hrs 4-12 hrs 4-13 hrs	10 6 9 4	Air saturation with both air and heliox excursions; no problems
1979	Facilities Test	Swedish Naval Diving Center	0.3-0.4	98	5	3	
1979-80	Diver Exercise Studies	Norwegian Underwater Institute	0.3-0.4	98-121	12	12	
1979-81	AIRSAT III	USN Sub Med Res Lab	0.21	132	7	12	
1981-83	SUREX	Eckenhoff and Parker 1984	air	45,55,65	7	18	Study of no-stop excursions to surface
			air	65,75	7	6	

Table 16-1
(Continued)

Date	Project	Data Source	Breathing Gas or PO_2	Depth, fsw	Duration, Days	Team Size/ Total No. Participants	Comments Concerning Period of Saturation Exposure
1982	NISAHEX	Muren et al. 1984	0.42	197	11	6	Adaptation to narcosis observed. Heliox and trimix excursions conducted
1982	Duke-NOAA-Oceaneering Dive	Miller and Koblick 1984	0.4	165	9	10	Adaptation to narcosis observed
1982-83	AIRSAT IV	USN Sub Med Res Lab	0.21	132	5	18	
1984	MINISAT I	Eckenhoff et al. 1986	air	25.5	2	19	
1984	MINISAT II	Eckenhoff et al. 1986	air	29.5	2	15	
1985-86	AIRSAT V	USN Sub Med Res Lab	0.4	111, 70	5	6	Study of no-stop ascent distances in saturation
			0.4	111, 60	5	6	
			0.4	111, 55	5	4	Bends in three divers following step ascent from saturation depth
			0.4	111, 60	5	8	Bends in three divers following step ascent from saturation depth
			0.4	111, 65	5	5	
1986	REPEX I	Hamilton et al. 1988a	0.3	50	6.5	4	
1986	REPEX II	Hamilton et al. 1988a	0.3	80	6.5	4	
1986	REPEX III	Hamilton et al. 1988a	0.3	110	8.5	4	
1986-87	AIRSAT VI	USN Sub Med Res Lab	0.4, air	111, 132, 74	6	6	Study of no-stop ascent distances in saturation

Adapted from NOAA (1979)

For practical purposes, the state of saturation is reached in less than 24 hours. The techniques of saturation diving make use of the fact that, once the body's tissues have reached this equilibrium, they can safely remain saturated for long periods without increasing the diver' s decompression obligation.

From an operational standpoint, there are two principal factors in saturation diving, i.e., the depth at which the diver's tissues become saturated (called the storage depth), and the vertical range of depths over which the diver can move (termed the excursion depths). The storage depth determines the breathing mixtures that can be used, the possible range of vertical excursions the diver can undertake, and the decompression schedule to be followed; the storage depth should be selected to maximize the diver's effectiveness in the working depth range. When selecting a storage depth, both ascending and descending excursions should be kept in mind, although descending excursions have several safety and operational advantages.

16.2 BREATHING GASES

Several different breathing mixtures have been used successfully in saturation diving, e.g., air, nitrogen-oxygen, and helium-oxygen. These mixtures may be used singly or in combination, both as the habitat gas at storage depth and as the breathing gas for excursions from the habitat.

Air has been used extensively as a breathing gas in saturation diving. Its use as a habitat gas is limited to relatively shallow depths (50 fsw; 15 m) because of oxygen toxicity (Adams et al. 1978). Short excursion dives from the storage depth have been conducted successfully to depths as great as 250 fsw (76 m) using air as the breathing medium. Because oxygen toxicity and nitrogen narcosis are both concerns on air dives to such depths, excursions using this breathing medium must be planned carefully.

NOTE

Because of the gas exchange characteristics of nitrogen and helium, saturation and saturation-excursion diving involving switches from one inert gas to another should not be attempted without the advice of a qualified person who has a thorough knowledge of the factors involved.

Several successful laboratory and at-sea saturation programs have been carried out at storage depths of 60 fsw (18 m) using air as the breathing medium. These dives have revealed physiological responses that, although apparently normal and reversible adaptations, suggest that operational air-saturations should be limited to 50 fsw (15 m; see Table 15-1). There is also some indication that habitation at this oxygen partial pressure (PO_2) level (i.e., that of air at 60 fsw (18 m); $PO_2 = 0.59$) may predispose divers to central nervous system (CNS) oxygen toxicity (Miller 1976) and that such an oxygen partial pressure may reduce a diver's tolerance for oxygen during any subsequent treatment for decompression sickness (Adams et al. 1978). Because the use of air has obvious advantages, research on its use as a breathing medium at depth will continue.

Shallow-water saturation diving also has been conducted using **nitrogen-oxygen** (nitrox) mixtures. The proportions of oxygen and nitrogen in nitrox mixtures are selected to provide a partial pressure of oxygen within a range from 0.21 ATA (close to the normal atmospheric value) to 0.50 ATA. Such mixtures can be used for habitat depths equal to or shallower than 50 fsw (15 m) and should be used for habitat depths greater than 50 fsw (15 m). Based on extensive military and commercial saturation diving experience with helium-oxygen gas mixtures, the optimal saturation oxygen partial pressure range is 0.30 to 0.40 ATA, with a nominal value of 0.35 ATA considered acceptable for all applications.

If the oxygen partial pressure of air at the saturation depth is too high, it can be adjusted by adding either nitrogen or low-oxygen nitrox mixtures or by allowing the oxygen in the habitat to be "breathed down" by the divers. If the oxygen partial pressure is above the recommended maximum level, care must be taken to ensure that the divers do not experience oxygen toxicity as a result of breathing hyperoxic gas in the habitat and during their air excursion dives. Consequently, breathing down the oxygen concentration is not acceptable in most situations and can only be used in very small habitats.

Divers engaged in excursion diving using air as the breathing medium must continuously be aware of the danger of oxygen toxicity (see Section 3.3). They must know the maximum amount of time that can be spent safely at various depths without incurring problems related to oxygen exposure. As with other toxicities, oxygen poisoning is a function of both dose and duration of exposure.

Although neurological symptoms, such as convulsions, are the most serious consequence of oxygen poisoning, the symptoms most likely to be associated with over-exposure in saturation-excursion diving are pulmonary. Accordingly, pulmonary tolerance limits that are safe for repeated daily exposures have been incorporated into the limits shown in Table 15-1 and have also been applied (where appropriate) to the tables in this section on saturation diving.

The degree of oxygen exposure can be quantified by using a system that permits pulmonary oxygen toxicity to be correlated with reduced vital capacity. The oxygen dose that causes a 10 percent reduction in vital capacity is considered the maximum safe cumulative oxygen dose, and diving operations should be planned so that every diver has a safety margin that will allow him or her to be treated for decompression sickness with oxygen without exceeding this 10 percent level.

Nitrox breathing mixtures have been used to depths of 198 fsw (60 m) in the laboratory, but the safe limit for such exposures has not been established, and nitrox saturation dives have been conducted in the open sea to depths as great as 111.5 fsw (34 m). To date, open-sea saturation dives that have used nitrogen-oxygen mixtures as the storage gas have employed air as the breathing gas for excursion dives. A review of the data gathered during these exposures reveals that

- The limiting factor when air is used as the saturation storage gas is oxygen partial pressure.
- The limiting factor when a nitrogen-oxygen mixture is used as the storage gas is nitrogen narcosis.
- Extended exposure (for as long as 11 days) to air at 50 fsw (15 m; 0.5 ATA PO_2) has not produced irreversible or deleterious effects on human volunteers (Adams et al. 1978).
- Extended exposure (27 days) to air at 60 fsw (18 m; 0.589 ATA PO_2) has caused significant decreases in red blood cell mass and, in some but not all individuals, a significant decrease in lung vital capacity, which indicates pulmonary oxygen toxicity (Miller 1976).
- The degree of nitrogen narcosis varies among individuals.
- Partial adaptation to narcosis may occur in some individuals after continued exposure.
- Prolonged exposure to normoxic nitrogen at depths to 120 fsw (37 m) has not produced a significant decrement in diver performance.

Based on this information, the following recommendations can be made for air and nitrox saturation dives:

- Air saturation should be limited to a depth of 50 fsw (15 m).
- The oxygen partial pressure of nitrogen-oxygen mixtures used in saturation storage gases should be kept within the range of 0.3 to 0.5 ATA.
- The operational use of nitrogen-oxygen as a storage gas should be limited to a depth of 120 fsw (37 m).

Helium-oxygen has been used widely as a breathing medium by the U.S. Navy and the commercial diving industry for saturation and excursion diving. (Readers should refer to the U.S. Navy Diving Manual (1987), the diving physiology literature, and Section 15.1.3 for information on this type of diving.) In general, helium-oxygen is selected as a breathing gas in surface-oriented diving when the job to be done requires that work be performed at a depth of 150 fsw (45 m) or more. The principal reason for using a helium-oxygen mixture is the avoidance of nitrogen narcosis (see Section 3.2.3.5). Helium mixtures have rarely been used as breathing gases for excursions from nitrogen saturation exposures; under some circumstances, isobaric bubble disease (the counterdiffusion phenomenon) could occur when these two gases are used (D' Aoust 1977; see Section 3.2.3.3).

16.3 LIFE SUPPORT CONSIDERATIONS

Excursion diving from a saturation system or habitat usually is performed with standard diving equipment, e.g., scuba, umbilical, or closed-circuit rebreathers. Because this equipment is described elsewhere in this manual, the following discussion describes the life support features of the saturation system itself.

Life support equipment and techniques vary greatly from one system to another. Some systems require complicated gas mixing and monitoring equipment on a surface support vessel, while others can be supported by equipment that supplies compressed gas, power, and environmental control from an unmanned buoy. Other systems, such as the mobile lockout submersibles commonly used by the offshore oil and gas industry, require a self-contained life support system.

The characteristics that a particular saturation diving life support system must have depend on the depth, mission duration, water temperature, sea surface condition, requirements for mobility, type of equipment to be used for excursions, rescue potential, and, in many cases, the nature of the work or scientific program to be carried out. Regardless of the system and its peculiarities, all divers must become familiar with the function of each system component, the system's maintenance requirements, and all emergency procedures. Training programs usually provide this information and offer an opportunity for such familiarization. However, all saturation systems have some features in common that relate directly to the health and safety of divers.

In saturation diving, the oxygen pressure for storage should be maintained between 0.30 and 0.50 ATA. Carbon dioxide levels should not exceed a sea level equivalent of 0.5 percent (0.005 ATA) (US Navy 1987). Carbon monoxide should not exceed a partial pressure that is equivalent to 0.002 percent by volume (20 ppm) at sea level. If air is the breathing gas, safe partial pressures of carbon dioxide can be maintained by constantly venting the interior atmosphere at a rate of 2 cfm for each diver at rest and 4 cfm for each diver not at rest (U.S. Navy 1988). Control of the oxygen partial pressure usually is not a problem at shallow depths when air is used as both the storage and excursion diving gas.

In closed-circuit life support systems and diver-carried rebreathers, which usually use mixed gases, carbon dioxide buildup is a significant problem, and a carbon dioxide scrubbing system is therefore necessary. The active ingredient in scrubbing systems is a chemical, usually composed predominantly of barium hydroxide (Baralyme®), lithium hydroxide, or soda lime (Sodasorb® or other trade name), that will absorb the carbon dioxide. The length of the absorbent's active life depends on the CO_2 output of the divers, the ambient temperature, and the relative humidity. The man-hour rating of a particular absorbent is provided by the manufacturer. Table 16-2 summarizes the characteristics of barium hydroxide, lithium hydroxide, and soda lime. Because carbon dioxide absorption is influenced by temperature, less CO_2 is absorbed at 40°F (4.4°C) than at 70°F (21.1°C). Some scrubbers sized for adequate performance at 70°F (21.1°C) may have only one-third of their absorbing capacity at 40°F (4.4°C).

Providing external insulation and heating scrubbers that are to be used in cold water are ways of minimizing the size of the canister that must be carried and ensuring that the absorbent achieves its design efficiency. Insulation and heating also minimize moisture condensation.

The efficiency of CO_2 absorbents also is influenced by relative humidity. Barium hydroxide and soda lime absorbents can only achieve their rated capacity when the relative humidity is above 70 percent. Lower humidity levels reduce absorbent capacity. Under conditions of high gas humidity and low scrubber surface temperature, water may condense on the walls of the canister or in the absorbent, which reduces absorptive capacity and increases pressure drop through the canister.

An auxiliary habitat scrubbing system frequently is used as a backup in case the primary system fails. If no backup scrubber system is available, the chamber should be vented as described above. Divers must remain alert for symptoms of carbon dioxide poisoning (changes in breathing rate or shortness of breath, headache, sweating, nausea, or weakness); the onset of such symptoms is sometimes difficult to detect over a long period. Divers also may not be aware of CO_2 buildup because they associate minor breathing difficulties with the greater density typical of breathing gases under pressure.

In addition to atmospheric control, a satisfactory life support system must have adequate controls for temperature and humidity. At shallow depths, comfortable temperature and humidity ranges are 78 to 83°F (25.6 to 28.3°C) and 50 to 75 percent, respectively, in air or nitrogen/oxygen environments. At deeper depths or in helium-oxygen saturation atmospheres, temperatures as high as 92°F (33.3°C) and a relative humidity between 40 and 60 percent may be necessary for comfort.

The atmosphere's relative humidity affects both the comfort and safety of chamber inhabitants. Habitat humidity is controlled by air conditioning and the use of dehumidifiers or moisture absorbers. Excessive humidity not only decreases scientific productivity but encourages the growth of fungus or bacteria that cause infections (see Section 3.2.1.1). On the other hand, humidity that is too low can create a fire hazard.

16.4 OPERATIONAL CONSIDERATIONS

Saturation divers working from a habitat or PTC have direct access to the work site. Use of the saturation mode greatly extends a dive's bottom time or working time because it reduces the relative amount of time that divers must spend compressing and decompressing. Saturation divers also find this mode psychologically advantageous because they find it convenient and reassuring to have a dry chamber close at hand.

16.4.1 General Procedures

A diver undergoing saturation on the seafloor for the first time has much to learn. First and foremost, the diver must learn that the surface is not a haven in an emergency; instead, refuge must be found at the working depth. Also, saturated divers must:

- Learn to rely on the surface support team for support;
- Be aware that the entire saturation, from predive preparation to the long decompression at the end of the mission, demands substantial commitment;
- Become familiar with the saturation system, its operation, all emergency procedures, and all fire safety rules;
- Become familiar with the diving equipment and its limitations;
- Become familiar with the surrounding area of the seafloor, the transect lines, and any other orientation markers;
- Learn the limits and procedures for making vertical excursions;

Table 16-2
Characteristics of Three
Carbon Dioxide Absorbents

Characteristic	Absorbent Barium Hydroxide	 Lithium Hydroxide	 Soda Lime
Absorbent density, lb/ft^3	65.4	28.0	55.4
Theoretical CO_2 absorption, lb CO_2/lb	0.39	0.92	0.49
Theoretical water generated, lb/lb CO_2	0.41	0.41	0.41
Theoretical heat of absorption, BTU/lb CO_2	670[1]	875[1]	670[2]
Useful CO_2 absorption, lb CO_2/lb (based on 50 percent efficiency)	0.195	0.46	0.245
Absorbent weight, lb per diver hr (0.71 lb CO_2)	3.65	1.55	2.90
Absorbent volume, ft^3 per diver hr	0.0558	0.0552	0.0533

[1] Based on calcium hydroxide reaction only.
[2] Based on generating gaseous H_2O.

Source: NOAA (1979)

- Plan all missions and excursions in advance, taking into account the equipment, saturation system, depth, excursion profiles, and the saturation experience of other team members; and
- Assume responsibility both for their own and their buddy's safety during excursions.

16.4.2 Emergency Procedures (Habitats)

All well-conceived saturation operations should have contingency plans that chart a course of action in case a primary life support system fails or another emergency arises. Any contingency plan should give first priority to diver safety. In a habitat or PTC, any emergency, however minor, threatens diver safety. The following emergency procedures are intended to serve as general guidelines that apply to all habitats and personnel transfer capsules. However, because most habitats and PTC's are one-of-a-kind systems, certain differences in hardware and design will dictate specific procedures that should be followed for each.

WARNING

Complete Emergency Procedures Should Be Developed for Each System, and All Surface Support Personnel and Divers Should Become Familiar With Them

Fire Safety

Fire probably is the most critical emergency that can threaten divers using a saturation system. Habitats using air as the storage medium are susceptible to fire because air supports combustion more readily under increased pressure. Burning rates under hyperbaric conditions are primarily a function of the percentage of oxygen present (Shilling et al. 1976). Atmospheres that have less than 6 percent oxygen will not support combustion. A normoxic nitrogen-oxygen habitat atmosphere contains a lower percentage of oxygen than an air-filled habitat and therefore presents a lesser fire hazard. When helium is used at great depths, the potential for fire is even further reduced. Care must be taken, however, when oxygen is used during decompression or treatment for decompression sickness.

For diving operations conducted outside the zone of no combustion (see Section 6.5.2), materials that are highly combustible should not be placed in the habitat. In the event of fire, divers should follow the general procedures below, although their order may vary:

- Make a quick assessment of the source of the smoke or flame. (If the source is a movable item, eject it from the habitat immediately, if possible.)
- Don emergency breathing masks.
- Shut off all power except lights and emergency communications.
- Notify surface personnel.
- Attempt to extinguish the fire with water.
- Attempt to remove all flammable materials from the immediate area of the flames. Also attempt to discharge smoldering material from the chamber.
- Leave the chamber after donning diving gear unless you are directly involved in fighting the fire.
- If the fire goes out of control, abandon the chamber, notifying surface personnel of this action if conditions permit. Proceed to available underwater stations and await surface support.

Loss of Power

Most shallow water habitat systems have a primary power source and an emergency or standby power source. Primary power is usually 110 volts a.c.; emergency power is usually 12 volts d.c. In some systems, the emergency power is designed to activate automatically if the primary source fails.

In a power emergency, divers should perform the following procedures:

- Activate the emergency power source, if this system is not automatically activated;
- Notify surface support personnel and stand by to assist in isolating and remedying the cause of the failure.

Loss of Communication

Most saturation systems have a backup communication system. Sound-powered phones that require no external power often are used. In some cases, communication over diver communication circuits may be possible. When a communication failure occurs, communication should be established immediately on a secondary system, the surface should be notified of primary system failure, and attempts should be made to reactivate the primary system.

Blowup

Inadvertent surfacing, commonly called blowup, is a serious hazard facing saturated divers, especially when they are using self-contained equipment and are not physically attached to a habitat or PTC by an umbilical or tether. Saturated divers who are away from the habitat must be careful to avoid any circumstance that would require them to make an emergency ascent to the surface or that might result in accidental surfacing.

If a diver does surface accidentally, however, the buddy diver must:

- Immediately return the diver to the saturation depth. If the accidental surfacing was caused by equipment failure, the diver's buddy should swim immediately to the surface and bring the surfaced diver down, using the emergency octopus regulator, and should then proceed to the habitat. If the saturation depth is greater than 100 fsw (30 m), the surfaced diver should be rescued by the surface support team, because a saturated buddy who surfaces to help the diver will also be endangered.
- Notify surface support personnel immediately.
- At depths of 60 fsw (18 m) or less, have the diver begin breathing pure oxygen while awaiting instructions from surface support; if deeper, an enriched oxygen mixture should be used to provide an oxygen partial pressure of between 1.5 and 2.5 ATA.
- Make preparation for emergency recompression, if directed to do so by surface support personnel.

NOTE

A diver who accidentally surfaces or becomes lost is in great danger. The best assurance against such emergencies is strict adherence to carefully planned preventive measures.

Lost Diver

A saturated diver working away from a habitat or PTC should be aware continuously of his or her dependence on that facility for life support. Any excursion should be planned carefully so that the way back to the chamber is known and assured. As in all diving, buddy divers are a necessity. In the saturated condition, it is especially necessary for diving buddies to stay close together and to be aware at all times of their location, significant landmarks, and the distance and direction back to the habitat or PTC. Many habitats, particularly those permanently fixed and continually used, have navigation lines extending to various underwater areas. Divers should become familiar with these navigation patterns and use them as reference points during excursions.

WARNING

Saturation Divers Should Place Primary Reliance for Orientation on Established Navigation Lines. A Compass Should Be Used Only to Provide a Backup Orientation System

If a diver becomes lost, he or she should take the following actions:

- Begin signaling by banging on his or her scuba cylinder with a knife, rock, or other hard object;
- To conserve breathing gas, ascend to the maximum upward excursion depth limit that still permits the bottom to be seen clearly (in murky water or at night, this will not be possible);
- If lost at night, switch his or her light off momentarily to look for the habitat or buddy's light;
- Begin making slow circular search patterns, looking for familiar landmarks or transect lines.

Divers hopelessly lost at saturation depths shallower than 100 fsw (30 m) should ascend slowly to the surface while they still have sufficient air. On reaching the surface, the diver should take a quick (less than 30 seconds) compass sighting on the support system or buoy over the habitat and should then return to the bottom, rejoin his or her buddy, and proceed directly to the habitat.

WARNING

Divers Should Start Their Return to the Habitat From Excursion Dives Before the Pressure in Their Cylinder Falls Below the Amount That Will Support Them During Their Return

Night Diving

Night excursions from habitats are common, particularly for scientific divers wishing to observe marine life. Divers must take special care not to become lost during these excursions. Every diver must be equipped with two well-maintained lights that are in good working condition and are equipped with fresh batteries. Every diver should also have an emergency light, preferably a flashing strobe. In emergencies, the strobe can be used for navigation if the diver shields his or her eyes from the flash. To assist divers back to the habitat if their lights have failed, a flashing strobe should be located on the habitat or PTC.

Decompression Sickness After Excursions

Although excursions from a habitat are not likely to cause decompression sickness, habitat operational plans should include procedures for treating decompression sickness. Specific procedures will vary from one habitat program to another, but the following general guidelines can be used if decompression sickness occurs after an excursion dive.

Therapy should be carried out in the habitat. The treatment of choice, as always, is recompression and the breathing of enriched oxygen mixtures (PO_2 1.5 to 2.5 ATA). If recompression is not possible, treatment using oxygen breathing and the administration of fluids and drugs should be attempted under medical supervision. Recompression in the water should be used only as a last resort. Decompression from saturation should be delayed for at least 36 hours after a diver has been treated for decompression sickness.

16.4.3 General Health Practices

The health and welfare of aquanauts living in an open, semi-closed, or closed environmental system are of prime importance to maintaining high performance in an underwater program. The micro-organisms that are associated with habitat living may impair the performance of divers to the point where the divers must be removed from the program; it is therefore essential to maintain a proper balance among the indigenous microflora. To maintain this balance, certain health practices should be followed. Although different underwater programs may require different practices, depending on the habitat and local conditions, observance of the general procedures that follow will help to maintain the health of saturation divers.

- Do not allow a person with a cold, ear infection, severe skin problem, or contagious disease to go into the habitat or to have contact with any diver who is to go into the habitat.
- Do not allow any medicines into the habitat that have not been approved by the responsible physician.
- Maintain the habitat's humidity and temperature at proper levels.
- Ensure that divers wash thoroughly with soap and fresh water after the last excursion of the day.
- Have the divers wash the inside of their wet suits daily with soap and water.
- Treat divers' ears daily, in accordance with the instructions in Section 3.2.1.1.
- Treat any cut, abrasion, etc., no matter how small.
- Have divers remove wet equipment before entering the habitat's living quarters and store it away from the living quarters.
- Ensure that any food that has fallen into crevices, where it might decay, is cleaned up.
- Remove garbage from the habitat daily, because it is both a health and a fire hazard.
- Change bed linens and towels in the habitat at least twice a week.
- Prevent divers from staying in the water without proper thermal protection, because body temperatures can drop significantly even in tropical waters.
- When inside the habitat, ensure that divers wear warm, clean, and dry clothing (including footwear).
- Wash the interior of the habitat thoroughly after each mission with a solution of benzalkonium chloride (Zephiran®) or other comparable disinfectant.
- Wash the habitat's sanitary facilities and surrounding walls and floor thoroughly every day with a suitable disinfectant solution.

16.4.4 Hazardous Materials

To avoid atmospheric contamination, fires, and diver disability, equipment and materials that could be hazardous must be excluded from the habitat. Such hazardous materials fall into five general categories:

- Volatile materials, both liquids and solids;
- Flammables;

- Medications whose pharmacologic effects may be altered by pressure;
- Objects that cannot withstand increased pressure; and
- Ungrounded or otherwise hazardous electrical equipment.

Before beginning a habitat mission, all personal diving and scientific equipment should be submitted to the operations director for review and logging. To avoid difficulties, aquanauts should provide documentation for any equipment or materials whose safety is likely to be questioned. Table 16-3 presents a list of materials that are hazardous in habitat operations. This list is not exhaustive, and any doubtful materials should be screened carefully by qualified personnel before being allowed inside a habitat; factors such as mission duration and the habitat's scrubbing capability should be taken into account during this process. If substances that are necessary also have the potential to affect divers in the habitat adversely, safe levels, control methods, and monitoring procedures for the use of these materials should be established. In addition, all divers and topside staff should be made aware of the signs and symptoms of any exposure-related effects potentially associated with the use of these substances.

16.5 EXCURSION DIVING

Excursion diving from saturation in a habitat or DDC/PTC system requires special preparation and strict adherence to excursion diving tables. A diver who is saturated at one atmosphere (i.e., at surface pressure) can make dives (excursions) to depth and return directly to the surface without decompression as long as his or her body has not absorbed more gas during the dive than it can safely tolerate at surface pressure. Similarly, a diver who is saturated at a pressure greater than one atmosphere (i.e., at the habitat's pressure) can make excursions either to greater depths (downward) or lesser depths (upward) by following the depth/time limits of excursion tables. Many factors change the conditions of excursions (e.g., temperature, work load, equipment, the diver's experience); these factors must be considered when planning any excursion dive or decompression.

Specific procedures for both ascending and descending excursions from air or nitrox saturation can be found in Hamilton et al. (1988b), and the methods used to develop these procedures have been published in Hamilton et al. (1988a). Information on other procedures that have been used in the past to conduct excursions from air or nitrox saturation is available in earlier editions of the *NOAA Diving Manual* and in Miller (1976).

16.6 DECOMPRESSION AFTER AN AIR OR NITROGEN-OXYGEN SATURATION DIVE

The operational procedures for decompression after a saturation dive vary with different dive systems. In systems located at depths of 50 fsw (15 m) or less, the divers can swim to the surface, immediately enter a recompression chamber, recompress to the saturation depth, and begin decompression. This method is possible if the interval the diver spends on the surface before recompressing is less than 5 minutes and the storage depth is less than 50 fsw (15 m) (Edel 1969, Weeks 1972, Walden and Rainnie 1971). Other systems are designed to decompress divers in the habitat on the bottom, after which the divers swim to the surface (Wicklund et al. 1973). In other cases, the habitat can be raised to the surface and towed to a base on the shore, where decompression is completed and standby facilities are available (Koblick et al. 1974).

For decompressions after saturation in deep diving systems, divers usually are transferred to a surface decompression chamber in a personnel transfer capsule that is pressurized at the pressure of the storage depth. Decompression is then accomplished in accordance with standard procedures for that depth and the saturation breathing medium. Specific procedures for saturation decompression can be found in previous editions of the *NOAA Diving Manual* and in Hamilton et al. (1988b).

16.6.1 Diving After Decompression From Saturation Exposure

Divers who have completed a saturation decompression may be resaturated immediately. However, if a diver wishes to make non-saturation dives soon after completion of a saturation decompression, he or she must wait 240 minutes before qualifying in repetitive Group Z of the Residual Nitrogen Timetable for Repetitive Air Dives (see Appendix B). The Residual Nitrogen Timetable for Repetitive Air Dives should then be followed as directed, with the diver moving to successively lower repetitive groups after the intervals specified in the tables. Any dives undertaken within 36 hours after an air or nitrox saturation dive should be limited to a depth of 50 fsw (15 m) or shallower for a maximum exposure of 1 hour.

Example:

Time

0800 A diver surfaces from a completed saturation decompression; however, more coral specimens

Table 16-3
Hazardous Materials
for Habitat Operations

Flammables (Volatile)	Explosion/ Implosion Hazards	Volatile Poisons	Metals, Metalloids And Their Salts	Mood-Altering Drugs	Miscellaneous Materials
Acetones	Pressurized aerosol cans	Mercury	Mercury	Ethanol	Tobacco smoking materials of any kind
Gasoline	Flares of any kind or ignitables	Ammonia	Fluorides	Marijuana	Matches or lighters
Ethers	Signaling devices	Chlorine	Selenium	Sedatives	Newly made (un-aired) vinyl or styrofoam materials (their solvents, vinyl chloride and isocyanate, respectively, are very toxic)
Naphtha		Sulfur dioxide		Hallucinogens	Cosmetics or perfumed materials (deodorants)
Alcohols		Hydrogen sulfide		Tranquilizers	Concentrated acids or bases
		Halogenated hydrocarbons		Ataractics	
		Aromatic hydrocarbons		Hypnotics	Adhesives, including wet suit cement
		Formalin		Anti-depressants	
				Stimulants	

Derived from NOAA (1979)

located at 50 fsw (15 m) are needed. How long must the diver wait before he or she may go to 50 fsw (15 m) for 30 minutes without incurring a decompression obligation?

1200 After waiting 240 minutes, the diver is in repetitive Group Z. The Residual Nitrogen Timetable for Repetitive Air Dives specifies that 2 hours and 18 minutes must be spent at the surface for the tissues to have released sufficient nitrogen to permit a 34-minute dive to 50 fsw (15 m) (which will place the diver in repetitive Group H).

1418 The diver dives to 50 fsw (15 m) for 30 minutes and surfaces without decompressing.

16.6.2 Flying After a Saturation Decompression

After a saturation decompression, divers should wait for at least 48 hours before flying. Observance of this rule greatly reduces the likelihood that such divers will experience decompression sickness.

SECTION 17
UNDERWATER SUPPORT PLATFORMS

UNDERWATER SUPPORT PLATFORMS

17

17.0 GENERAL

During the last two decades, new technology and a better understanding of the physiology of diving have made saturation diving available as a method of accomplishing extensive work under water. With the development of this new method of diving, underwater support platforms have become common in commercial diving and are becoming increasingly valuable in scientific studies and underwater archaeology. Underwater support platforms include manned habitats, work shelters, diving bells, lockout submersibles, flooded submersibles, remotely operated vehicles, and one-atmosphere diving systems.

17.1 PRESSURIZED DIVING BELL SYSTEMS

Although most underwater habitats are fixed on the seabed and cannot be transported with divers inside, semi-mobile underwater support platforms, which are known as diving bells, have proven their worth in several types of undersea tasks. A diving bell usually is only one part of an integrated system (Figure 17-1) designed to provide divers with a dry, safe living environment that can be maintained for long periods at or near the pressure prevailing at the dive site itself. A diving bell functions as a dry, pressurized, and sometimes heated elevator to transport divers between surface living quarters and underwater work sites. While the divers are on the bottom, the nearby diving bell functions as a tool storehouse and ready refuge. Most diving bells are capable of carrying and supporting 2 to 4 working divers.

On board the support ship or barge are the deck decompression chamber(s), control van, and other supporting machinery, such as electric generators, hydraulic power systems, and hot water generators. Normal living operations and decompression are carried out in the deck decompression chamber.

When beginning a job, divers enter the bell and are lowered to the work site. After reaching the required depth, the divers equalize the bell pressure with the outside seawater pressure, open the lower hatch, and exit to start work. If necessary, the bell can be moved closer to the job site by maneuvering the ship. Upon completion of the task, the divers re-enter the bell and are raised to the surface, where the bell is mated to the deck decompression chamber. In the deck decompression chamber, the divers remain at depth and prepare for their next trip to the work site. With one or more teams, this cycle can continue for days or weeks if necessary. Decompression is carried out after completion of the mission. Bell diving systems offer advantages over a fixed habitat if a large bottom area is to be covered or if heavy tools and substantial surface support are required. Under saturated conditions, one or more teams of divers can live in relative comfort in the deck chamber. Hot meals can be passed in, and surface personnel can maintain direct contact with the divers. Commercial bell diving systems are designed to be operated between 200 and 1500 fsw (61 and 457.3 msw).

Today, most work done from diving bells is in support of the offshore oil industry. Additionally, the various navies of the world use bell diving systems for salvage, search and recovery, and instrument implantation.

17.2 OPEN BELL SYSTEMS

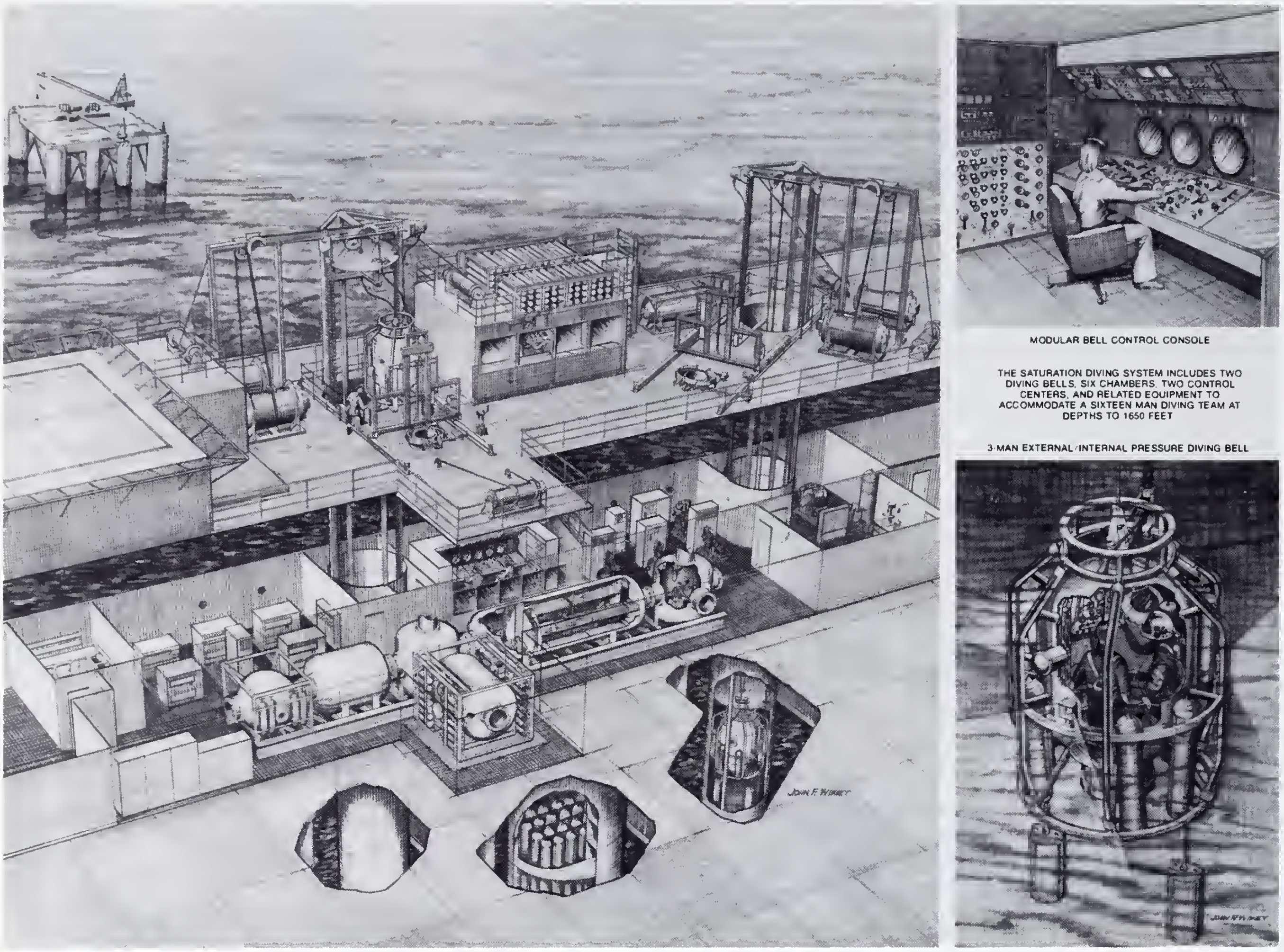
17.2.1 Description

The open bottom bell, referred to as a Class II or non-pressurized bell, was developed as an in-water work platform and emergency way station. Unlike a diving stage, which serves only as an elevator between the surface and the work site, the open bottom bell provides a semi-dry refuge, emergency breathing gases, and communications capability.

The bell consists of a rigid frame with an open grating on which the diver stands and an acrylic hemispheric dome that is open on the bottom. By adding suitable breathing gases to the inside of the dome, water is forced out, creating a dry gas bubble for the diver's head and shoulders. The acrylic dome is transparent, which affords the divers a full field of vision. Ballast is added to the bottom of the bell to make it negatively buoyant in the water (Figure 17-2).

Emergency breathing gases are supplied to the bell from two separate sources: one from a topside umbilical and another from high-pressure gas cylinders mounted on the outside of the bell. Both gases are routed to a manifold inside the dome and used for

Figure 17-1
Saturation Diving Complex



Courtesy Saturation Systems

dewatering the bell dome and emergency breathing via built-in-breathing (BIB) masks or scuba regulators. A speaker mounted in the dome allows two-way voice communication with topside personnel.

The bell is raised and lowered by a wire cable from a crane, davit, or A-frame on the support vessel. A life support umbilical consists of a hardwire communication cable, gas supply hose routed from a surface control manifold, pneumofathometer hose providing continuous depth readouts at the surface, a strength member in case the primary lift cable breaks, and additional specialty components as required (Figure 17-3).

17.2.2 Operational Parameters

Although typically used in support of surface-supplied diving, the open bell may be used in conjunction with many types of diving operations. When supporting surface-supplied diving operations, the diver's umbilical is routed from the surface rather than from the bell. Most open bells can support two divers in normal operations and three divers in an emergency; however, they are often designed and built for specific purposes in various sizes and weights. Safe operation of an open bell requires a stable support platform capable of holding its position in a variety of sea conditions.

OSHA and United States Coast Guard (USCG) regulations require the use of an open bell on all dives deeper than 200 fsw (61 msw) or those involving more than 120 minutes of in-water decompression, except when a heavy-weight diving outfit (full helmet with a constant-volume dry suit) is used or when dives are being performed in a physically confining space. These regulations also allow open bell use to a depth of 300 fsw (91 msw) in helium-oxygen diving operations; in actual practice, however, the use of open bells is usually restricted to 225-250 fsw (70-75 msw) because of limited emergency support capabilities. Longer and

Figure 17-2
Open Diving Bell on Deck of Seahawk

Courtesy NURC-UNCW

deeper dives are more safely performed using a closed and pressurized diving bell.

17.2.3 Operational Procedures

Operation of an open bell requires completion of a rigorous predive checklist of all major support systems, including the bell-handling, life-support, and communications systems. Positive control of the bell is essential during deployment and retrieval and requires the use of control lines (Figure 17-4). The bell is lowered into the water, shackled into a separate downline to prevent the bell from turning during ascent and descent, and all control lines are removed. Divers enter the water, secure themselves on the outside of the bell, and prepare to descend. Riding the bell in this position rather than being transported inside the bell prevents the divers from being trapped inside if the lift cable breaks.

During ascent and descent, the bell and diver's depth and rate of travel are monitored and controlled by topside personnel via a control panel. Compressed gases are added to the bell dome during ascent to exclude water. Descent is stopped when the bell is 10-15 feet (3-4.5 meters) from the bottom, and the bell remains suspended in the water column while the divers are on the bottom. Whenever they leave the bell, the divers vent the dome to reduce the buildup of carbon dioxide, because an emergency return to the bell may require the divers to breathe the gas inside the dome while they don their emergency breathing equipment. The divers pass their umbilicals through the legs of the bell to help them to relocate the bell at the conclusion of the dive.

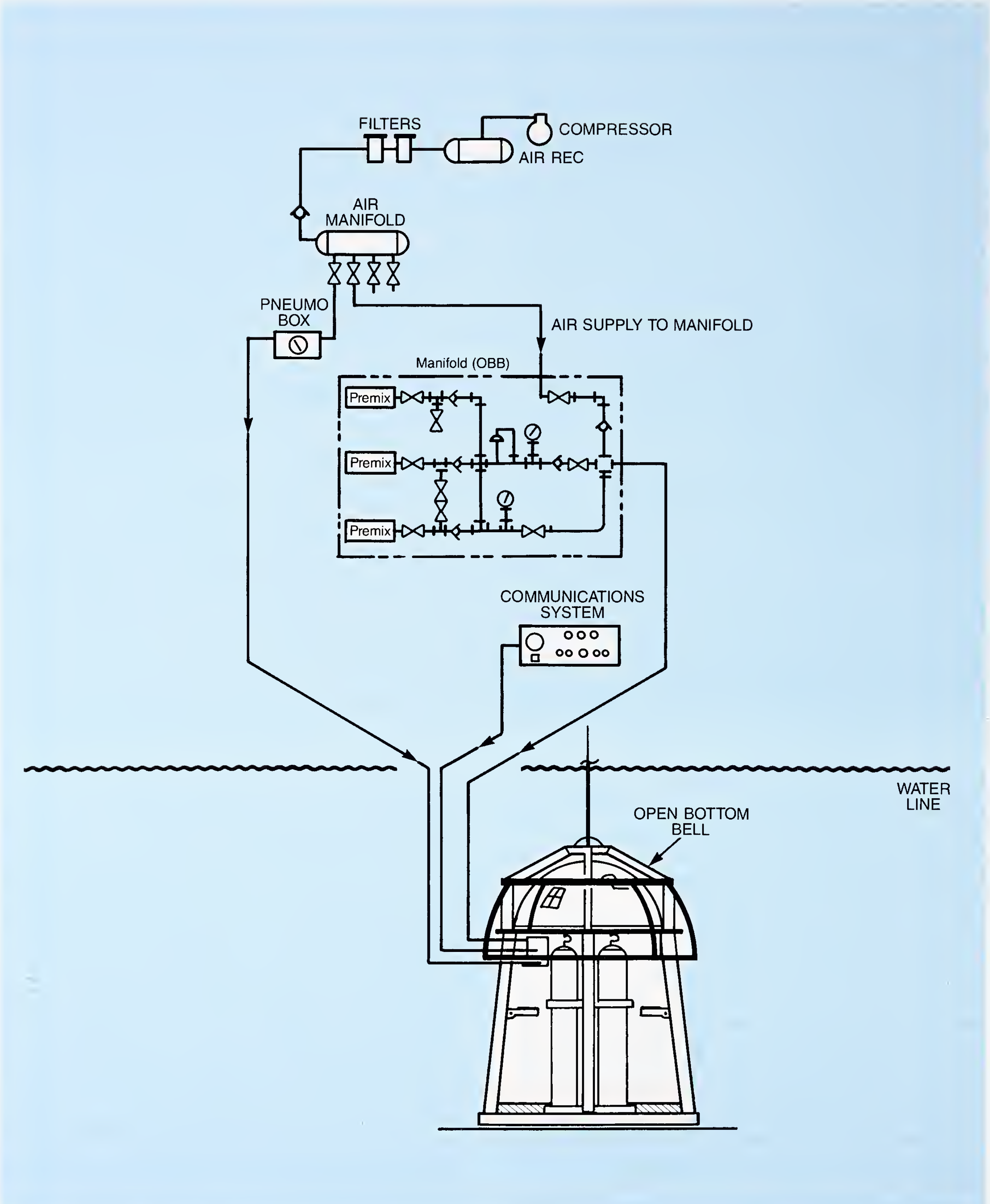
During ascent, the bell is raised at the appropriate rate of speed and is stopped at predetermined depths in accordance with the appropriate decompression schedule. After the last in-water decompression stop, the bell is brought to the surface, the divers climb aboard the support platform, and any further decompression is completed on board.

Retrieval of the bell reverses the steps in the deployment procedure, except that a surface swimmer must enter the water to attach the control lines and unshackle the bell from its downline. The bell is lifted aboard and secured to the deck. All systems are rechecked for proper operation, gas supplies are inventoried, gas banks are charged, and maintenance is performed in preparation for the next dive (Figure 17-5).

17.3 DIVER-LOCKOUT SUBMERSIBLES

Most research submersibles have one or two compartments designed to maintain the crew at a pressure of one atmosphere. All allow direct observation through viewing ports or acrylic spheres. Many research submersibles have manipulators that permit the occupants to collect samples and place equipment on the seafloor. Others have lockout capabilities that permit divers to leave the submersible. Lockout submersibles have a separate chamber that can be pressurized to ambient pressure so that the divers may enter and exit while the pilot and other personnel remain at atmospheric pressure within the submersible (Figure 17-6). When locking out, the diver is usually tethered to the submersible by an umbilical that provides hardwire communication to the submersible and a gas supply that can be either a primary or backup breathing source. With lockout capability, scientists have the choice of directing collections from the observation compartment or locking out from the dive chamber and collecting the samples. A diver-lockout submersible also affords great mobility, reduces unnecessary in-water time for the divers, allows decompression to be initiated soon after the di-

Figure 17-3
Bell System



Courtesy David A. Dinsmore

Figure 17-4
Open Bell Showing Control Lines

Courtesy NURC-UNCW

ver returns to the vehicle, and permits the divers to be transported from site to site under pressure. Generally, decompression is managed and controlled by a dive controller positioned in the one-atmosphere compartment of the submersible. Some lockout submersibles can be mated to deck decompression chambers. This allows the diving team to saturate in the chamber on deck and to be transported to the work site via the submersible. Also, in the case of deep, long exposures, most of the decompression can be carried out in a larger, more comfortable environment.

The value of the lockout submersible to the scientist lies in its high maneuverability in three planes, its mobility, and its ability to provide shelter for long periods at depth. Lockout submersibles can cruise at atmospheric pressure until they arrive at the dive site. The pilot can station the submersible so that the work site is directly in front of the pilot compartment before locking the diver out. During the lockout, both the pilot and dive controller can observe the activities of the diver. If there is a need to investigate an area where the depth prohibits diver lockout, the lockout submersible can serve as an observation vehicle. Remotely operated collection tools, manipulators, and cameras can be used to enhance observation in this mode.

Although diver/scientists normally do not pilot the submersible themselves, they must be familiar with its capabilities and operating procedures. A detailed orientation schedule must be developed prior to any operation, and training must include at least one shallow-water excursion so that the diver/scientist can learn to operate all high- and low-pressure systems and become familiar with decompression and emergency procedures. Lockout submersibles always have space in the diving chamber for at least two divers. A general practice is to pair a member of the submersible's crew with a scientist so that a well-trained crew member can act as a tender when the scientist is in the water. Using the submersible in this manner allows a scientist with a good diving background but little or no previous lockout experience to use the facility to best advantage, without actually becoming a full member of the submersible's crew. The scientist performing work in the water is in most cases monitored visually and via voice communication by the submersible pilot or dive controller. In-situ ecological observations can be made concurrently with the lockout dive, using external still or movie cameras and videotape systems.

17.4 FREE-FLOODED SUBMERSIBLES

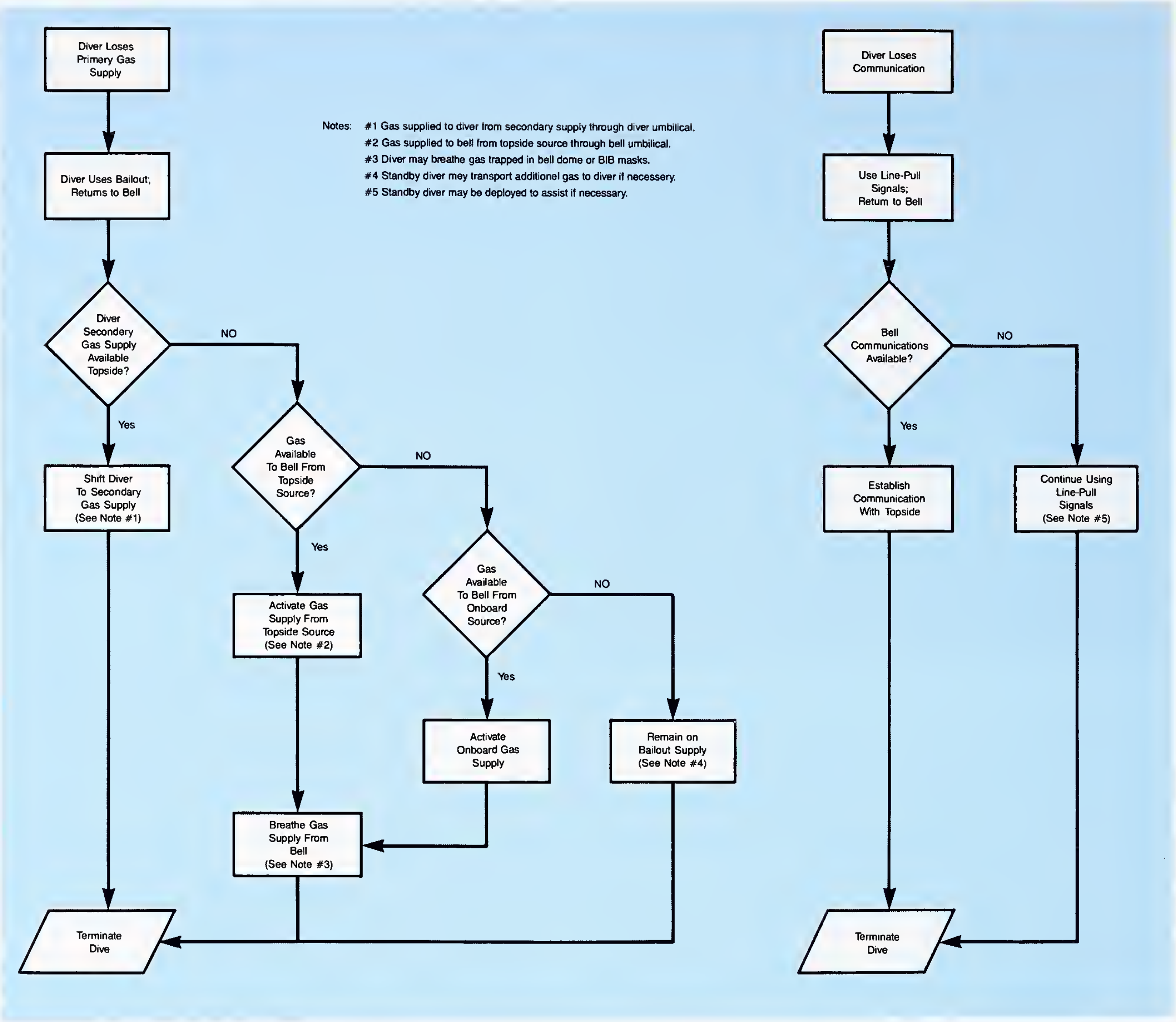
Although conventional one-atmosphere and diver-lockout submersibles require a pressure-resistant hull, a free-flooded submersible (wet sub) can be thought of as an underwater convertible. When in use, these vehicles are full of water and the divers breathe by using scuba equipment. This equipment can be open-circuit, semi-closed, or closed-circuit and may be worn on the back or mounted in the vehicle, depending on the nature of the mission and the design of the submersible.

There are several configurations of wet subs. In some, as many as four divers sit one behind the other, while others are designed to have divers side by side, either sitting or in the prone position. These vehicles are used primarily for transporting divers at speeds of up to 4 knots (2 m/s) to conserve time and air and to assist diver/scientists in conducting ocean floor surveys. They also can be used as small underwater pickup vehicles. Wet subs are excellent vehicles for all kinds of survey work because they can cover large areas carrying still and television cameras as well as divers. However, most wet subs require extensive maintenance.

In planning for operations involving wet subs, certain factors must be considered:

- Training in general operating procedures, especially in obstacle avoidance, is essential.
- When making long excursions with a wet sub under normal diving conditions, a buoy should be used to permit easy tracking by a surface support boat.

Figure 17-5
Open Bell Emergency Flow-Chart



Notes: #1 Gas supplied to diver from secondary supply through diver umbilical.
#2 Gas supplied to bell from topside source through bell umbilical.
#3 Diver may breathe gas trapped in bell dome or BIB masks.
#4 Standby diver mey transport additionel gas to diver if necessery.
#5 Standby diver may be deployed to assist if necessary.

Courtesy David A. Dinsmore

- Because a diver can be lulled easily into a false sense of security, bottom time and depth must be monitored carefully.
- A good compass mounted on the sub is essential for navigation.
- Wet sub divers will get cold faster because they are essentially motionless in the water and thus generate little body heat.
- Wet sub use under saturated conditions requires careful consideration of current velocity, direction, and reserve air supply to ensure that a diver could swim back to the habitat should the sub's propulsion system fail.

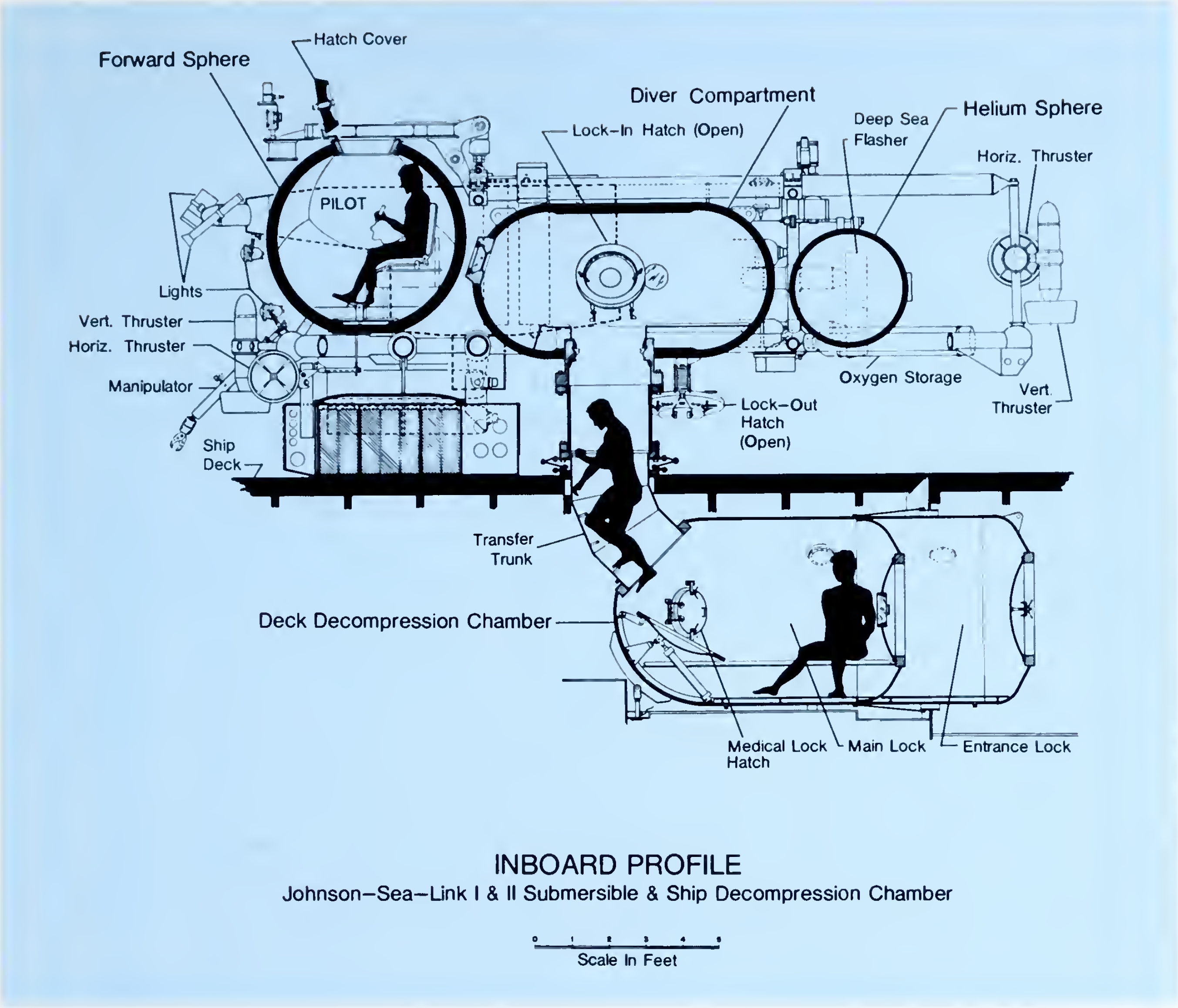
WARNING

When Using Either a Wet Sub or Swimmer Propulsion Unit Under Saturated Conditions, Precautions Must Be Taken To Avoid Accidental Ascent

17.5 UNDERWATER HABITATS

Early underwater habitats were designed primarily to evaluate engineering feasibility or to demonstrate human capability to survive in the undersea environment. They

Figure 17-6
Cutaway Showing Mating Position
With Deck Decompression Chamber



Source: NOAA (1979)

were not designed to accommodate the average scientific diver, nor could they be emplaced or moved easily. Since 1962, over 65 habitats have been utilized in 17 countries throughout the world (Figure 17-7) (Miller and Koblick 1984). They have been used for observation stations, seafloor laboratories, and as operational bases for working divers.

Underwater habitats provide diving scientists with unlimited access to defined areas of the marine environment, enabling them to make observations and to conduct experiments over long periods of time in the saturation mode. Because habitats are open to ambient pressure, the blood and tissues of the aquanauts become saturated with the gas they are breathing, and decompression is required only at the end of a mission.

Habitats come in many shapes and sizes; the degree of comfort of these underwater quarters varies from spartan to luxurious. Habitats have consisted of an arrangement as simple as a rubberized tent with a single cot; in contrast, some have been four-room apartments. A University of New Hampshire survey (1972) describes those features of an underwater habitat that users consider desirable (Table 17-1).

When designing and selecting habitats for marine science programs, technical, logistic, and habitability criteria must be applied if systems are to facilitate mission objectives. Important considerations include simplicity, functionality, and comfort. An aquanaut-scientist who is constantly wet, cold, crowded, and miserable for days at a time cannot be expected to

Figure 17-7 Undersea Habitat Specifications and Operational Data

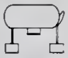
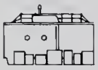
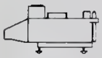
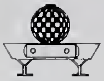
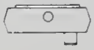
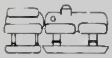
	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)	Size (m)	Weight (Tons)	Habitat Gas	Surface Support	Mobility	Decompression (Hours)	Remarks
	Adelaide	Australia	1967-1968				14+				Ship raft			From pontoons
	Aegir	U.S.A.	1969-1971	Hawaii	24-157	4-6	14	2 cyl., 2.7 × 4.6 plus 3m sphere	200	N_2/O_2 He/O_2	Ship	Towable		Can ascend and descend by internal control
	Asteria	Italy	1971	Lake Garda	50					Air He/O_2				Diver training, instrument testing
	Atlantik	Italy	1969	Lake Cavazzo	12	4		L=7 W=2	44 Displ. Each	Air	Shore			3 separate habitats Primary compressor located on seafloor
	BAH-I	Federal Republic of Germany	1968-1969	Baltic	10	2	11	L=6 D=2	20	N_2/O_2	Ship	Readily movable		
	Balanus	USSR	1968	Japanese Sea	5			H=5.5 D=1.2	5	Air	Shore			Observation chamber
	Bentos-300	USSR	1966	Sevastopol	300	24	14	L=21 W=5.5 H=11.2	500	Air He/O_2	Ship buoy	Self-propelled		Only self-propelled habitat
	Bubble	U.K.	1966	Malta	10	2-3	1	D=2.1 Sphere	8 Bal.	Air	Shore	Readily movable	0	Decompression experiments
	Caribe-I	Cuba-Czech	1966	Rincon de Guanabo near Havana	20	2	3	L=3.5 D=1.5	6 Bal	Air	Ship	Readily movable		First Eastern Bloc habitat
	Chernomor-I	USSR	1968	Black Sea	5-14	4-5	4-6	L=7.9 D=2.9	62 Displ.	Air	Ship	Towable		
	Chernomor-II	USSR	1969-1974	Black Sea	5-31	4-5	14-52	L=8 D=3	74 Displ	Air N_2/O_2	Ship	Towable	Varied	Modified Chernomor-I
	Conshelf-I Diogenes	France	1962	Marseilles, Mediterranean Sea	10	2	7	L=5.2 D=2.4		Air	Ship Shore	Readily movable	3	
	Conshelf-II Starfish House	France	1963	Shaab Rumi Reef, Red Sea	11	5	30	10.4 4 legs 1.2·2.4	100 Bal.	Air	Ship	Readily movable	2.5	
	Conshelf-II Deep Cabin	France	1963	Shaab Rumi Reef, Red Sea	27.4	2	7	D=2.0		50% He 50% Air	Ship	Towable	3.5 from 27.4 m to 11 m	
	Conshelf-III	France	1965	Mediterranean Sea	100	6	22	D=5.5 sphere	130+	2.5% O_2 97.5% He	Ship	Towable	84	Mounted on 8.5 × 14.6 m barge
	Edalhah	U.S.A.	1968 1972	Alton's Bay, N.H.; Miami, Fla.	12.2 13.7	3	3-5	L=3.6 D=2.4	14 25	Air	Shore ship	Readily movable	19	
	Erebos	Czech	1967-1968	Olsany	11.5	2		L=2.7 W=1.3 H=1.8	15 Bal	Air	Shore	Readily movable		Deployed in quarry
	Galathee	France	1977		Approx. 18	5	2	L=7 W=6.6 H=4.8	7	Air	Ship			
	Geonur	Poland	1975-1976	Gdynia	50	4		H=7.6 W=4.2	34		Ship	Towable		For geology
	Glaucus	U.K.	1965	Plymouth	10.7	2	7	W=2.1 L=3.6	13	Air	Shore	Readily movable	3.0-3.5	Decompression experiments
	Hehros-I (Khebros)	Bulgaria	1967	Lake Varna	7	2	7	L=5.5 D=2.0		Air	Shore	Towable		Made from a locomotive boiler
	Hebros-II	Bulgaria	1968		30		10	W=2.5 L=6.7			Shore			Not known if used
	Helgoland-I	Federal Republic of Germany	1969	North Sea	23	2-4	5-11	L=9.0 D=6.0	75	N_2/O_2	Buoy	Readily movable	Varied	
	Helgoland-II	Federal Republic of Germany	1971 1977	North Sea Baltic, USA	22-31	4	4-14	L=13.8 W=6.0	102	N_2/O_2	Buoy	Towable	Varied	Modified Helgoland-I

Figure 17-7
(Continued)

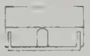
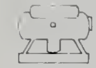
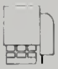
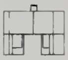
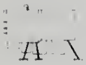
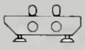
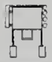
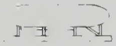
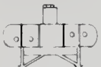
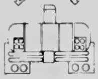
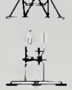
	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)	Size (m)	Weight (Tons)	Habitat Gas	Surface Support	Mobility	Decompression (Hours)	Remarks
	HUNUC	South Africa	1972	Durban	10	4	N/A	L=5.9 W=1.5		Air	Shore	Movable		Sank during emplacement—never occupied
	Hydrolab	U.S.A	66-70 70-74 75-84	Florida Bahamas Virgin Islands	12-18	2-4	7-14	L=4 9 W=2.4	40	Air	Buoy	Towable	13-20	Most utilized habitat in the world
	Ikhtiandr	USSR	1966	Crimean Coast Black Sea	12	3	7	L=2.2 W=1.6 H=2.0	10 Bal.	Air	Shore	Readily movable		
	Ikhtiandr	USSR	1967	Crimean Coast Black Sea	12.2	2-5	7	3 cubes L=8.6 H=7.0		Air	Shore	Readily movable		2 female aquanauts
	Ikhtiandr	USSR	1968	Crimean Coast Black Sea	10	4	3			Air	Shore	Readily towable		
	Karnola	Czech	1968		8 15	5	3-7	H=7.0				Readily movable		
	Kitjesch (Kitezh)	USSR	1965	Crimean Coast	15	4		L=6.3 W=2.2	25		Shore			Made from a converted railroad tankcar
	Klobouk (Hat)	Czech	1965	Koza-rovice	6	4	Daily visits	L=1.2 H=1.0		Air	Shore	Readily movable		
	Kockelbockel	Netherlands	1967	Sloterplas	15	2-4	Short period	D=1.9 H=4.6	9.5+	Air	Auton-omous	Readily movable		
	La Chalupa	U.S.A	1971-1974	Puerto Rico	15-30	4-5	14	2 cyl. 2.4×6.0 1 rm 3×6	150	N_2/O_2	Buoy	Readily movable	36-48	Farthest operation from shore
	Lakelah	U.S.A	1972	Grand Traverse Bay, Michigan	15.2	2	2	D=3 0 H=2.1	24 Bal.	Air	Shore	Readily movable	N/A	
	LORA	Canada	1973-1975	New-foundland	7.9	2	1	L=2.4 D=4 9	24 Bal.	Air	Shore	Fixed	0	Under ice
	LS-I	Rumania	1967	Lake Bicaz	12-14	3-4	30	L=7.2 D=2.4	20 Bal.	Air	Ship	Readily movable	48	Still used for observation
	Malter-I	German Democratic Republic	1968-1983	Malter Dam	8	2-4	2-7	L=4.2 D=2.0	14	Air	Shore	Readily movable		Under ice
	Man-in-Sea I	U.S.A.	1962	Mediterra-nean	61	1	1	L=3.2 D=0.9	2.1 incl Bal.	3% O_2 97% He	Ship	Readily movable	65.5	World's first open sea saturation
	Meduza-I	Poland	1967	Lake Klodno	24	2	4	L=2 2 W=1 8 H=2.1	3.0	37% O_2 63% N_2	Shore	Readily movable	53.5	Entire habitat raised for decompression
	Meduza-II	Poland	1968	Gdansk, Baltic Sea	26	3	7	L=3 6 W=2.2 H=1.8	8	Air	Ship	Readily movable	22	Excursions to 50m
	Minitat	U.S.A.	1970	Virgin Islands	30.5	2	14	H=3.4 D=2.4	13.5 displ.	N_2/O_2	Ship	Towable	N/A	Never operational
	Neritica	Federal Republic of Germany/ Israel	1977	Eilat, Red Sea	9	2-3	16	L=3.4 W=2.0	3	Air	Shore	Readily movable	14	
	Permon-II/III	Czech	1966 1967	Bruntanya	10	2	3	L=2.0 W=2 0		N_2 O_2	Shore	Readily movable		
	Portalab	U.S.A.	1972	Rhode Island	11.3	2	<1	L=2.4 W=1 8 H=2 1	7 2 Bal	Air	Shore	Readily movable	0	
	Rohinsub-I	Italy	1968	Ustica Island	10	1	2	L=2 5 W=1 5 H=2.0	7.5 Displ.	Air	Shore	Readily movable		Wire cage/ plastic tent
	Sadko-I	USSR	1966	Black Sea, Sukumi Bay	12	2	6 hrs/ team	D=3 sphere	13.5	Air	Ship shore	Readily movable		Stationed in midwater
	Sadko-II	USSR	1967	Black Sea, Sukumi Bay	25	2	6	D=3 2 spheres	28.5 Bal.	N_2/O_2	Ship shore	Readily movable	70	Stationed in midwater

Figure 17-7
(Continued)

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)	Size (m)	Weight (Tons)	Habitat Gas	Surface Support	Mobility	Decom-pression (Hours)	Remarks
	Sadko-III	US5R	1969	Black Sea, Sukumi Bay	25	3*	14	D=3.0 H=15.0	30 Bal.	$He/N_2/$ $O/_2$	Ship	Readily movahle		Stationed in midwater
	SD-M	UK	1969	Malta	6-9	2	1-7	L=2.9 W=1.8 H=1.8		Air	Auton-omous			Rubber tent with steel frame
	Sealah-I	U.S.A (Navy)	1964	Argus Island Bermuda	58.8	4	11	L=12.2 D=2.7 H=4.5	20 Bal.	4% O_2 17%N_2 79% He	Ship	Movable	56	
	Sealah-II	U.S.A. (Navy)	1965	La Jolla, California	62.5	10	15-30	L=17.5 D=3.6 H=3.6	200	4% O 2S% N_2 71% He	Ship	Movahle	30	
	Sealah-III	U.S.A. (Navy)	1969	San Clemente, California	182.9	5-12	N/A	L=17.5 D=3.6 H=3.6		2% O_2 6% N_2 92% He	Ship	Movahle	N/A	Death of aquanaut caused cancellation
	Seatopia	Japan	1968-1973	Yokosuka	30	4	2	L=10.5 W=2.3 H=6.5	65	4.8% O_2 16.0% N_2 79.2% He	Ship	Movahle	66	Only used for one open-sea mission
	5elena-I	USSR	1972	Beloye Lake	11.5	1	15 hrs.	D=2.0 H=3.0	5	Air		Readily movahle		Semipermeahle membrane
	5helt-1	Bulgaria	1970	Burgas Gulf	20	3	4-5	L=6.0 D=2.5	30	Air	Ship	Readily movable	33.5	
	SPID (Man-in-Sea II)	U.S.A	1964 1974	Bahamas Canadian Arctic	131.7 4.3	2	1	L=2.4 W=1.2		3.6% O_2 5.6% N_2 90.8% He	Ship shore	Readily movable	92 0	Inflatable habitat
	Sprut (Octopus)	USSR	1966	Black Sea	10.S	3	14	D=5.0 sphere		Air	Shore	Readily movable		Inflatable habitat
	Sprut-M	USSR	1968	Black Sea	14	2		D=2.4		Air	Shore	Readily movable		Inflatable habitat
	Sprut-U	USSR	1969-1970	Black Sea	12-34	1-4				Air	Shore	Readily movahle		Inflatable habitat
	Suh-Igloo	Canada	1972-1975	Cornwallis Island	12.2	2-4	1	D=2.5 sphere	8 Bal.	Air	Shore	Readily movable	0	Under ice
	Suhlimnos	Canada	1969-	Georgian Bay, Ontario	10.1	2-4	Up to 24 hrs.	H=2.7 D=2.4	9	Air	Ship shore	Readily movable		Designed for day-long occupation
	5uny-lah	U.S.A	1976-	New York	12.2	2-3	1	1.5	6	Air	Ship	Readily movable		Made from cement mixer .
	Tektite I-II	U.S.A.	1969-1970	U.S. Virgin Islands	13.1	4-5	6-59	D=3.8 H=5.5	79	92% N_2 8% O_2	Ship shore	Fixed	19.5	World's longest open-sea saturation
	Xenie	Czech	1967	Adriatic	6	1	3	L=3.3 H=1.0 W=1.0	0.13	Air	Shore	Readily movable		

Note Bal = hallast, displ. = displacement

From Miller and Koblick (1984), with permission from Jones and Bartlett Publishers

perform efficiently or to produce scientific results of high quality. For a description of specific scientific projects accomplished to date using underwater habitats, consult Pauli and Cole (1970), Miller et al. (1971), Miller et al. (1976), Wicklund et al. (1972, 1973, 1975), Beaumariage (1976), or Miller and Koblick (1984).

17.5.1 Saturation Diving Habitats

More than 65 underwater habitats have been constructed throughout the world since 1962. Their level of sophistication ranges from the simple shelters described in Section 17.5.2 to large systems designed for extended seafloor habitation. The habitats used most extensively were *Chernomor* (Soviet Union), *Helgoland* (West Germany), and *Tektite, Hydrolab,* and *La Chalupa* (USA). The habitats described in this section were selected because they represent a cross-section of those built to date, and the programs in which they were utilized include most U.S. marine scientific saturation programs. Saturation diving habitats differ from work shelters in that they allow divers to stay on the seafloor long enough to become saturated (see Section 16.1). Decompression may be accomplished either inside the habitat or in a surface decompression chamber after an ascent made with or without a diving bell.

Edalhab (Figure 17-8) was designed and built by students from the University of New Hampshire as an

Table 17-1
Desirable Features of Underwater Habitats

Overall Size About 8 Feet x 38 Feet
(2.4 Meters x 11.6 Meters)

Separate Wet Room:
- Large entry trunk
- Wet suit rack
- Hot shower
- Hookah and built-in-breathing system
- Scuba charging
- Wet lab bench
- Specimen freezer
- Clothes dryer
- Diving equipment storage
- Rebreathers

Living Room:
- Bunks
- Microwave
- Food freezer and refrigerator
- Water heater
- Toilet
- Individual desk and storage
- Dry lab bench
- Compactor
- Library
- Tapes, TV, radio
- Emergency breathing system
- Computer terminal

GENERAL:
- Hemispheric windows
- Temperature and humidity control
- Separate double chambers
- On-bottom and surface decompression capability
- Suitable entry height off bottom
- Submersible decompression chamber for emergency escape
- External survival shelter
- External lights at trunk and viewports
- External cylinder storage and charging
- Habitat-to-diver communication
- Diver-to-diver communication
- Adjustable legs
- Mobility
- External or protected internal chemical hood

Adapted from NOAA (1979)

engineering project. The habitat was constructed mainly of salvaged and donated materials. The living quarters were enclosed in an 8 x 12 foot (2.4 x 3.7 meter) cylinder with a small viewing port at each end. The interior was insulated with 1.5 inch (3.8 centimeter) thick unicellular foam. Entry was made through a hatch centrally located in the floor. The interior had two permanent bunks (which folded to form a large seat) and a collapsible canvas cot. Communications, air, and power were provided from the support ship to the habitat through umbilicals. Decompression was accomplished by having the divers swim to the surface and immediately enter a deck decompression chamber. *Edalhab* had no specific facilities for scientific investigation, required a manned support ship, and was not easily moved from site to site.

Hydrolab (Figure 17-9) was designed to be simple and inexpensive to operate. The main structure was an 8 x 16 foot (2.4 x 4.9 meter) cylinder supported on four short legs and positioned 3 feet (0.9 meter) above a concrete base. It was submerged by venting and flooding ballast tanks and could be towed short distances for relocation in depths up to 100 feet (30.5 meters). Entry into the habitat took place through a hatch at one end that also functioned as a lock when the chamber pressure was below ambient pressure. The single room was furnished with three bunks, folding chairs, a dehumidifier, an air conditioner, a sink, and a table surface.

A self-contained, unmanned, 23 foot long (7 meter) life-support barge floated at the surface above the habitat and supplied, via an umbilical, all life support, including electrical power, high- and low-pressure air, and water. A small stand-up shelter was provided nearby for emergencies and to serve as an air filling station. More than 700 scientist-aquanauts have lived in *Hydrolab* since 1972. After almost 20 years of service, *Hydrolab* was decommissioned by NOAA in 1985, and the habitat is now on view in the Smithsonian's Museum of Natural History.

Tektite (Figure 17-10) was a four-person habitat consisting of two hulls attached to a base and connected by a cross-over tunnel. The two cylinders were each divided into two compartments, containing the control center, living quarters, equipment room, and wet room. The control center also served as a dry laboratory for scientists. The living quarters contained four bunks, a small galley, and storage and entertainment facilities. The equipment room contained the environmental control system, frozen food, and toilet facilities.

Air, water, electrical power, and communications were provided from the shore by means of umbilicals. The wet room was intended for scientific work; however, participants had difficulty entering with specimens in hand and found that most of the work space had been taken up with diving equipment and carbon dioxide absorbent. The dry lab in the control compartment served as an instrument room.

One or more hemispherical windows in each compartment and a cupola on the top of one cylinder allowed scientists to view the midwater and bottom areas adjacent to the habitat. Decompression was accomplished by having the divers enter a personnel transfer capsule on the bottom, raising them to the surface, and locking them into a deck decompression chamber.

La Chalupa (Figure 17-11) was a four-person habitat built as an underwater marine laboratory. Instead of a typical entrance tube, there was a 5 x 10 foot (1.5 x 3.0 meter) door in the wet room floor that allowed divers to enter and exit easily.

Large stainless-steel tables were provided in the wet room for sorting specimens; additional instrumentation space was provided next to a 42 inch (107 centimeter) window where scientific equipment could be used. The laboratory had a computer for data analysis. A special waterproof connector in the wet room

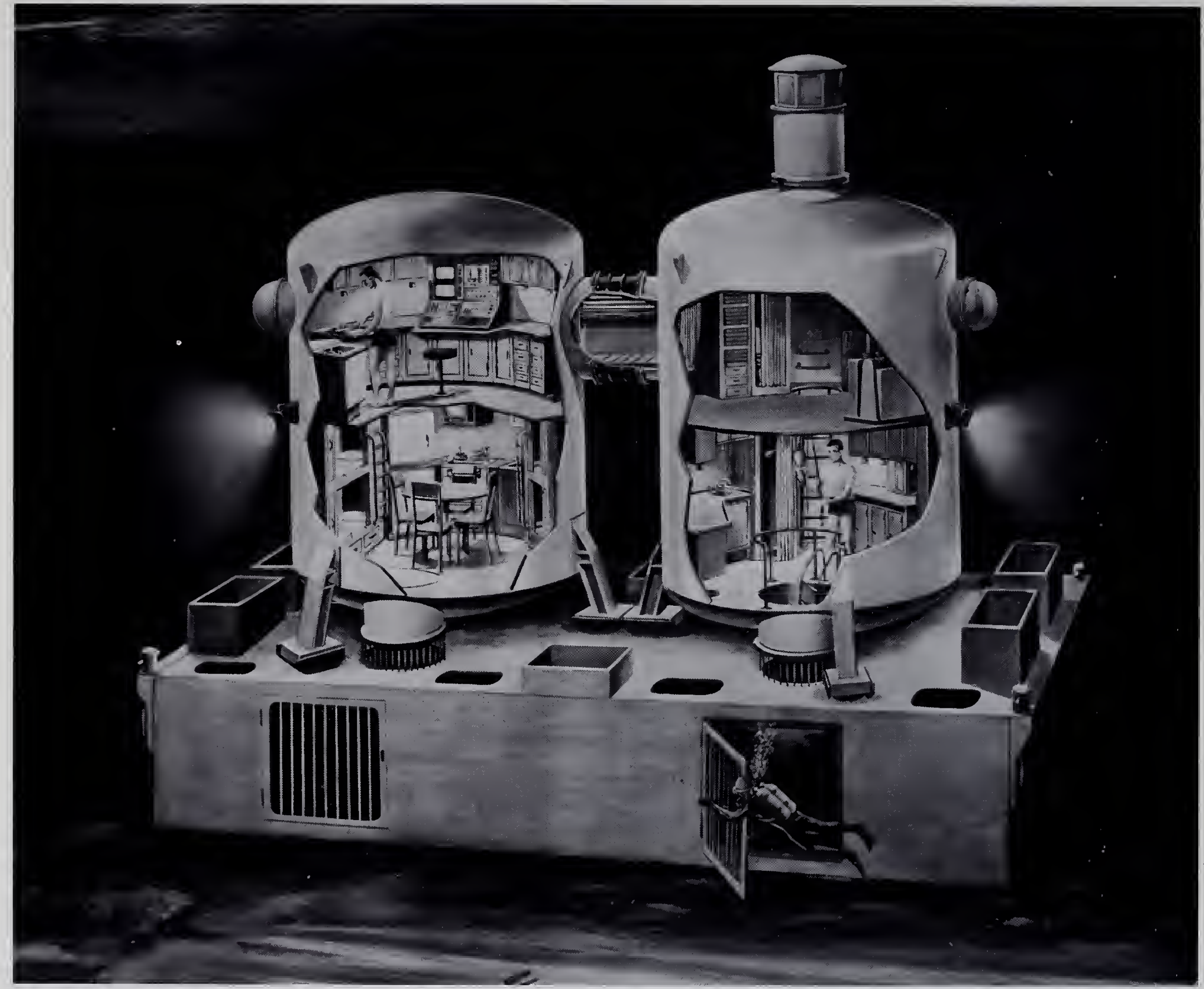
Figure 17-8
Edalhab

Source: NOAA (1979)

Figure 17-9
Hydrolab

Photo Dick Clarke

Figure 17-10
Tektite



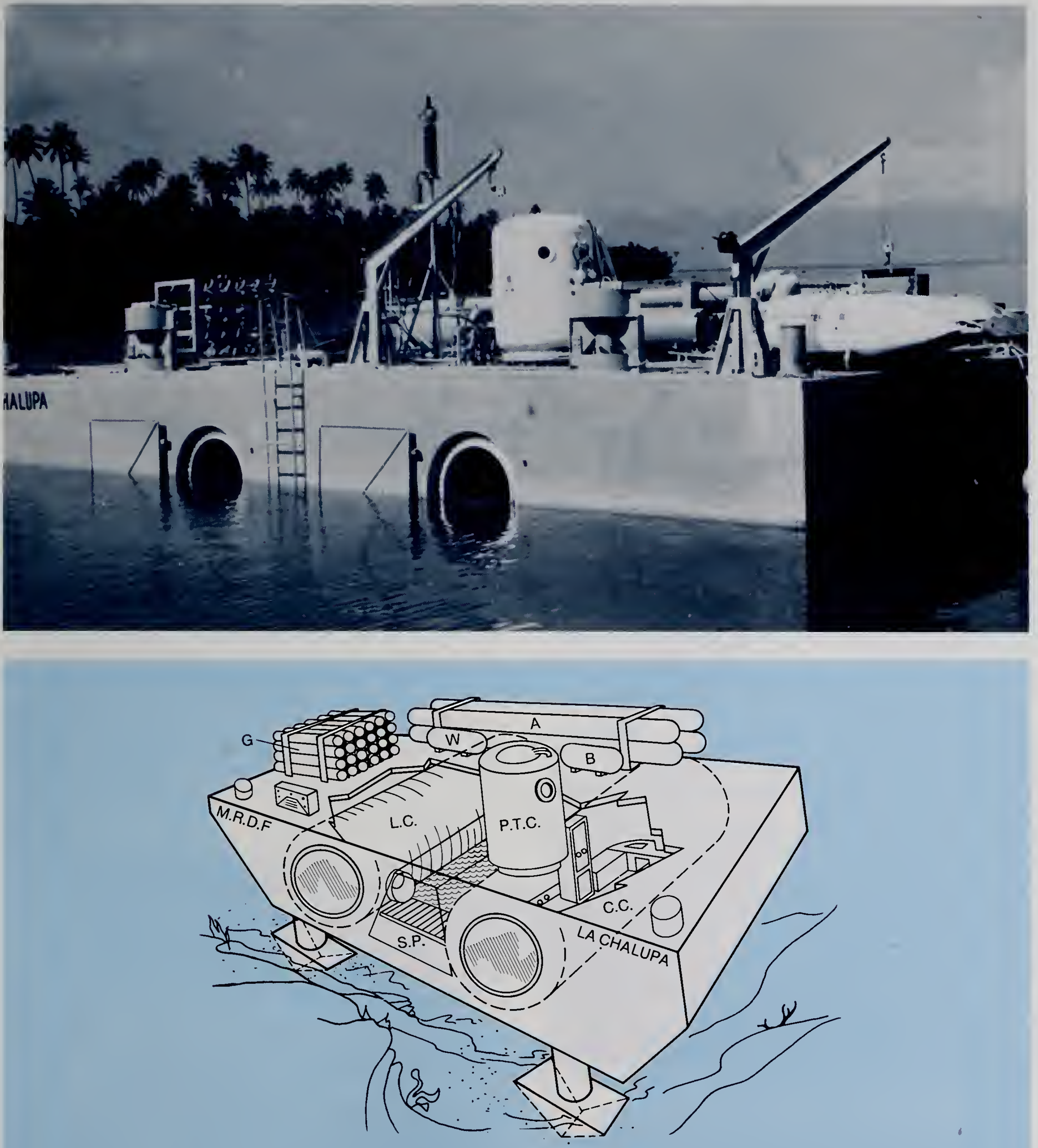
Courtesy General Electric Company

allowed instruments outside the habitat to have readouts for current, salinity, and water temperature in the control room. The habitat structure consisted of two 8 x 20 foot (2.4 x 6.1 meter) chambers within a barge; between the chambers was the 10 x 20 foot (3.0 x 6.1 meter) wet room.

La Chalupa was used at depths of 40 to 100 feet (12.1 x 30.5 meters) and could be moved easily from one location to another and emplaced in about 1 hour. Surface support was provided by a self-contained unmanned utility buoy that supplied power, water, high- and low-pressure gas, and communications. A pair of two-man submersible decompression chambers was attached to the habitat for emergency use; these could be entered, pressurized to gain buoyancy, and released from the main habitat. Once on the surface, the pressurized chambers could be transported by helicopter and mated to a shore-based decompression chamber. At completion of a mission, the habitat was brought to the surface and towed to shore while the aquanauts began decompression in the pressurized living compartment.

The *Aegir* habitat (Figure 17-12) was capable of supporting six divers at depths of up to 580 feet (176.8 meters) for as long as 14 days. The personnel chamber consisted of three compartments: living, control, and laboratory. The living and laboratory compartments were identical in size and shape, cylindrical with dished heads and an inside dimension of 9 x 15 feet (2.7 x 4.6 meters). The control compartment, located

Figure 17-11
La Chalupa



Living compartment (LC), control compartment (CC) and subport (SP) within the barge structure. On deck the high-pressure air (A), reserve water (W) and battery power (B), and two personnel transfer capsules (PTC) take up the remaining deck space. The whole structure is supported by four adjustable pneumatic legs.

Courtesy Marine Resources Development Foundation

Figure 17-12
Aegir

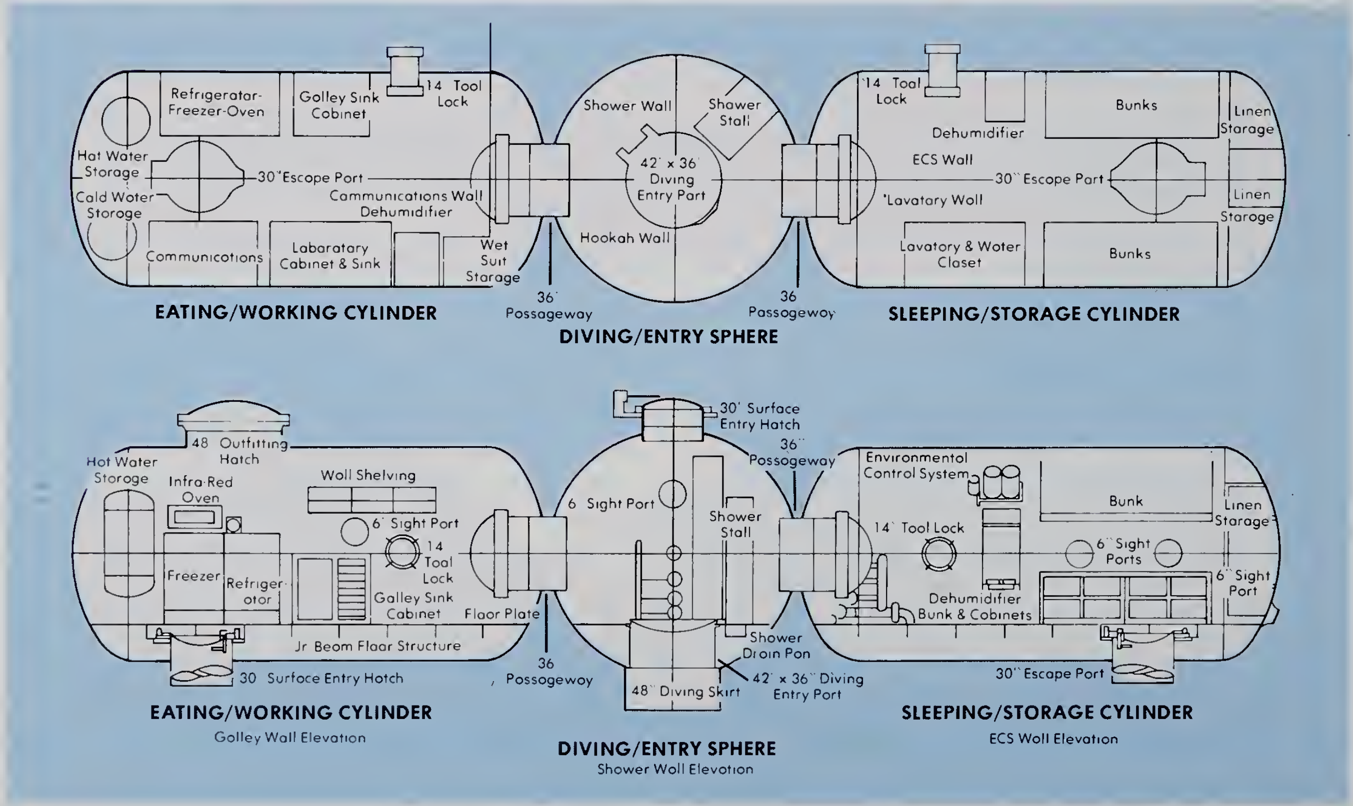


Photo Courtesy Makai Range

between the two cylinders, was spherical, with an inside diameter of 10 feet (3 meters). The three compartments were connected by two 36 inch (91.4 centimeter) in diameter necks. The support platform (twin 70 foot (21.3 meter) long pontoons, each 9 feet (2.7 meters) in diameter) was capable of controlling the ascent and descent of *Aegir* independent of surface control.

A support ship tended the habitat when it was submerged. At the completion of a mission, the habitat was brought to the surface while the aquanauts remained in the pressurized compartment. The habitat was then towed to shore for completion of decompression.

Of the 65 habitats built since 1962, only one currently is used regularly. This is a small underwater classroom located on Key Largo in the Florida Keys (Figure 17-13). Designed and constructed as an engineering project at the United States Naval Academy in 1974, this 8 x 16 foot (2.4 x 4.9 meter) habitat, now privately owned, is located in a mangrove lagoon at a depth of 20 feet (6.1 meters) and is used by students and researchers for missions lasting from 1 to 3 days. Normally occupied by 3 to 4 persons, the habitat has housed over 200 persons in the first 1 1/2 years of operation. Because of the shallow depth, decompression is not required after missions are carried out.

NOAA has recently constructed a new habitat named the *Aquarius* (Figure 17-14) for use at research sites throughout the Caribbean. This latest addition in the long line of habitats will operate at depths of up to 120 feet (36.6 meters) and will accommodate 6 scientist-aquanauts. Because of its mobility, the *Aquarius* can be moved to selected sites in response to the needs of scientific research.

17.5.2 Non-Saturation Habitats

Many diving projects require long periods of work or observation to be carried out in relatively shallow water. Simple underwater work shelters are useful on such projects; the primary function of these shelters is to allow divers to work for longer periods without surfacing, to protect them from the cold, and to serve as an emergency refuge and an underwater communication station. To be most effective, the shelter should be close to the diver's work site.

Underwater shelters vary in size and complexity, depending on the nature of the work and the funds available to provide support equipment and facilities. They can be made of materials such as steel, rubber, plastic, or fiberglass. Most of the shelters constructed to date consist of a shell designed to contain an air pocket, although some have been supplied with air from the surface or have used auxiliary air cylinders. Hardwire or acoustic communication systems have been used with some shelters. The decision to use work shelters should be based on considerations of ease of emplacement, operational preparation time, bottom working time, and cost-effectiveness.

The following are examples of four shelters that have been used successfully for scientific observation

Figure 17-13
Underwater Classroom

Photo ©Robert Holland, 1987

Figure 17-14
Aquarius

Photo R. Rounds

and studies. *Sublimnos* (Figure 17-15A) is a Canadian shallow-water shelter that was built for scientists operating on a tight budget. The shelter provided day-long underwater work capability for as many as four divers. The upper chamber was 9 feet (2.7 meters) tall and 8 feet (2.4 meters) in diameter. Entry was made through a 35 inch (88.9 centimeter) hatch in the floor of the living chamber.

Subigloo (Figure 17-15B), also Canadian, was used with great success in Arctic exploration programs in 1972 and 1974 and in the Caribbean in 1975. It consists of two 8 foot (2.4 meter) acrylic hemispheres on aluminum legs and permits an unrestricted view, making it an excellent observational platform. *Subigloo* is now used daily by divers as a part of 'The Living Seas' exhibit at Walt Disney's Epcot Center in Orlando, Florida.

Lake Lab (Figure 17-15C) was designed to be operated continuously for 48 hours by two people and to be emplaced at depths of up to 30 feet (9.1 meters). As with the other shelters, decompression was accomplished by having the divers swim to the surface and immediately enter a deck decompression chamber. Another type of support platform that is used on undersea research projects is shown in Figure 17-15D. This Undersea Instrument Chamber (USIC) houses instruments that record temperature, oxygen content, pH, light level, redox potential, conductivity, and sounds.

Figure 17-15A
Sublimnos

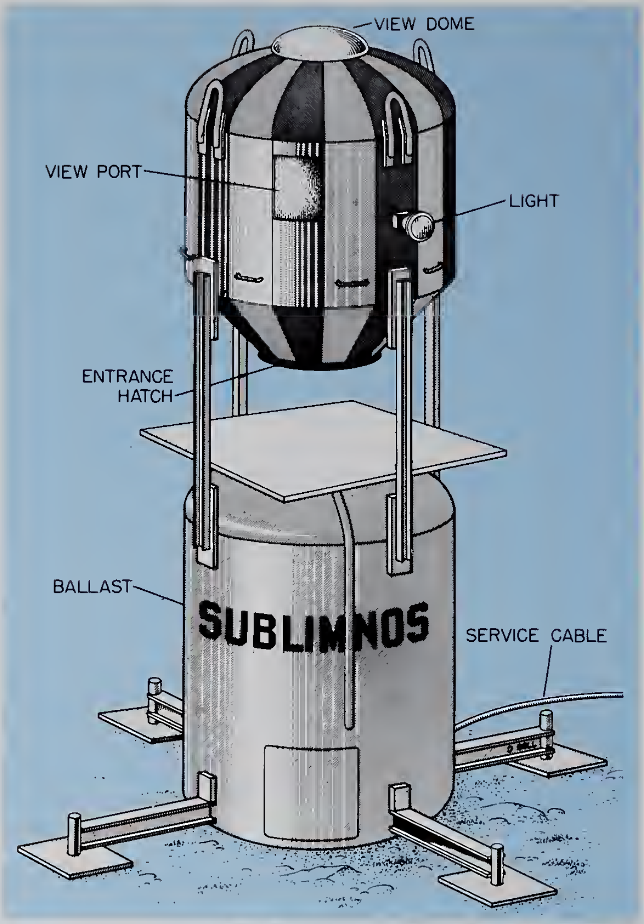


Illustration copyright 1969, Great Lakes Foundation

17.6 DIVER PROPULSION VEHICLES

Diver propulsion vehicles (DPV's) are useful for scuba divers who must make long-distance underwater surveys or travel long distances from a boat or shore base to an underwater work site (Figure 17-16). Basically, a DPV is a small hand-held cylinder with a propeller on one end that usually is constructed of aluminum alloy. The propeller is driven by an electric motor supplied with power from rechargeable batteries. The amount of thrust varies among models; however, one popular model delivers 30-35 pounds of thrust at full power. On some models, the thrust may be varied from 5 to 35 pounds. Two 12-volt batteries (in series) provide about 1 hour of operation at full power. The DPV is held by pistol-grip handles in front of and below the diver's body so that the thrust pushes the water under, and not in the face of, the diver.

17.7 ATMOSPHERIC DIVING SYSTEMS

The operational problems associated with work at great depths and biomedical considerations (decompression sickness and the high pressure nervous syndrome) have revived interest in atmospheric diving systems, which allow the operator to remain at one atmosphere regardless of the operational depth.

In 1969, the British developed the atmospheric diving system now referred to as JIM (Figure 17-17), which has undergone modification to achieve greater flexibility and depth capability. The new modified system is called SAM.

The advantages of one-atmosphere diving systems are largely biomedical, i.e., the elimination of decompression sickness and the risks associated with the high pressure nervous syndrome. The operational advantages of these systems include long bottom times at depth, greater repetitive dive capability, security, and protection from the cold at depth. Such advantages have been demonstrated in many open-sea operations over the last few years. One, and perhaps the most dramatic, was a dive in 1976 to 905 fsw (275.8 msw) in the Canadian Arctic through 16 feet (4.9 meters) of ice into 25°C seawater. An operator worked successfully for 5 hours and 59 minutes below the ice and experienced only minimal discomfort. To accomplish the

Figure 17-15B
Subigloo

Courtesy National Geographic Society

Figure 17-15C
Lake Lab

Photo Lee Somers

Figure 17-15D
Undersea Instrument Chamber

Photo Morgan Wells

same task using conventional diving methods (only the saturation mode could have been used) would have incurred a decompression obligation of more than 8 days; with JIM, however, no decompression was necessary, because the operator remained at a pressure of one atmosphere. The present JIM system has a magnesium alloy cast body; a new development is a JIM system constructed of carbon fiber steel. Equipping JIM systems with the aluminum articulated arms of the SAM systems has improved performance significantly. The record dive for JIM to date has been a working dive in the Gulf of Mexico to 1780 fsw (542.7 msw),where the JIM system worked in tandem with WASP (Figure 17-18), a manned diving system that allows the operator to perform midwater tasks. Like JIM, the WASP system can be used to perform motor tasks, such as shackling and threading nuts.

Compensating joints developed for the JIM system provide the flexibility for performing tasks that was lacking in earlier one-atmosphere systems. Future developments in atmospheric diving systems and other manned

Figure 17-16
Diver Propulsion Vehicle

Photo Dick Clarke

submersibles will include advances in manipulator technology, which will enhance human performance under water. Although these advances are not likely to permit divers to be replaced, they will augment the underwater performance of divers and allow them to concentrate on underwater tasks that require judgment, flexibility, and the ability to deal with the unexpected.

17.8 REMOTELY OPERATED VEHICLES

Remotely operated vehicles (ROV's) have become valuable adjuncts to divers in several ways: they allow the diver's bottom time to be increased and thus enhance productivity; they provide tools and instruments for underwater work assistance; and they can be helpful in an emergency.

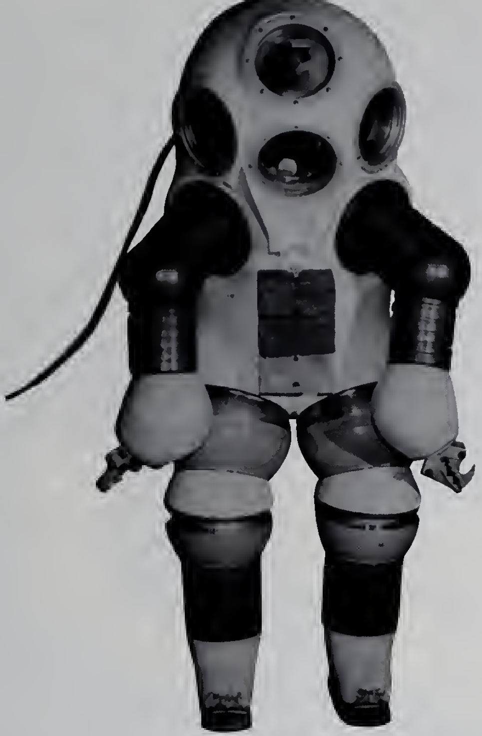
Although very few ROV systems are identical, the major components that comprise such systems are generally the same and are shown in Figure 17-19. There are over 106 different types of ROV's. They range in cost from about $27,000 (Figure 17-20) to well over $1 million, from the size of a basketball to that of a compact automobile, and in depth of operation from 98.4 feet (30 meters) to more than 9840 feet (3000 meters). In their simplest form, they provide free-ranging, mobile TV capability. In their more sophisticated form, ROV's provide complete assemblages of tools and instruments to conduct detailed bottom surveys, non-destructive testing (NDT) and cleaning of offshore structures, maintenance and repair of structures, and a variety of specialized tasks related to the offshore petroleum industry and the military. More recently, interest in using ROV's in scientific and other types of diving has increased.

The offshore oil industry has been the major user of ROV's for diver assistance. Virtually all of this use has been in connection with saturation diving operations, but the same methods can be applied to non-saturation diving. The following is a tabulation and brief description of the various support tasks ROV's have conducted.

Diving Support Ship Positioning Assistance

With a pinger or acoustic beacon attached to the ROV and a receiving hydrophone deployed from the surface ship, the ROV is launched to locate the exact position of the dive site. When the site is located, the

Figure 17-17
JIM System



Courtesy Oceaneering International, Inc. and U.S. Navy

Figure 17-18
WASP System

Courtesy Oceaneering International, Inc.

support ship is positioned directly over the vehicle and is anchored or holds station dynamically while the dive is conducted. This procedure offers two advantages: 1) the diver does not need to consume bottom time looking for the work site; and 2) the support ship can remain close to the diver in case an unscheduled return to the surface is required. In many instances, it is the practice to station the ROV at the work site with its lights on. The diver can then use the lights to home in on the job.

Evaluate Diving Conditions Related to Safety

Before deploying divers, the ROV is sent to the dive site to ascertain such aspects of the environment as visibility, currents, and man-made or natural hazards that might influence diver safety. This use of ROV's greatly enhances subsequent dive safety.

Evaluate Dive Site With Respect to Tooling

During predive reconnaissance, the ROV can be used to assess the work site and identify the tools that will be needed to conduct the job. The ROV can also help the diver to map out a technique to use when conducting the task. This procedure can save many trips back and forth to the surface and can also reduce the bottom time that is spent appraising the job.

Continuous Monitoring of the Diver for Safety

Industrial diving may be carried out at depths of up to 1000 fsw (304.9 msw). The knowledge that an ROV is positioned outside of the bell can be reassuring to divers. An ROV can be used to check the diver's gear for leaks and can then accompany the diver during the dive to provide immediate on-scene appraisal if the diver runs into trouble. In several instances, ROV's have been used to assist during the retrieval of dive bells that have been parted from their umbilicals.

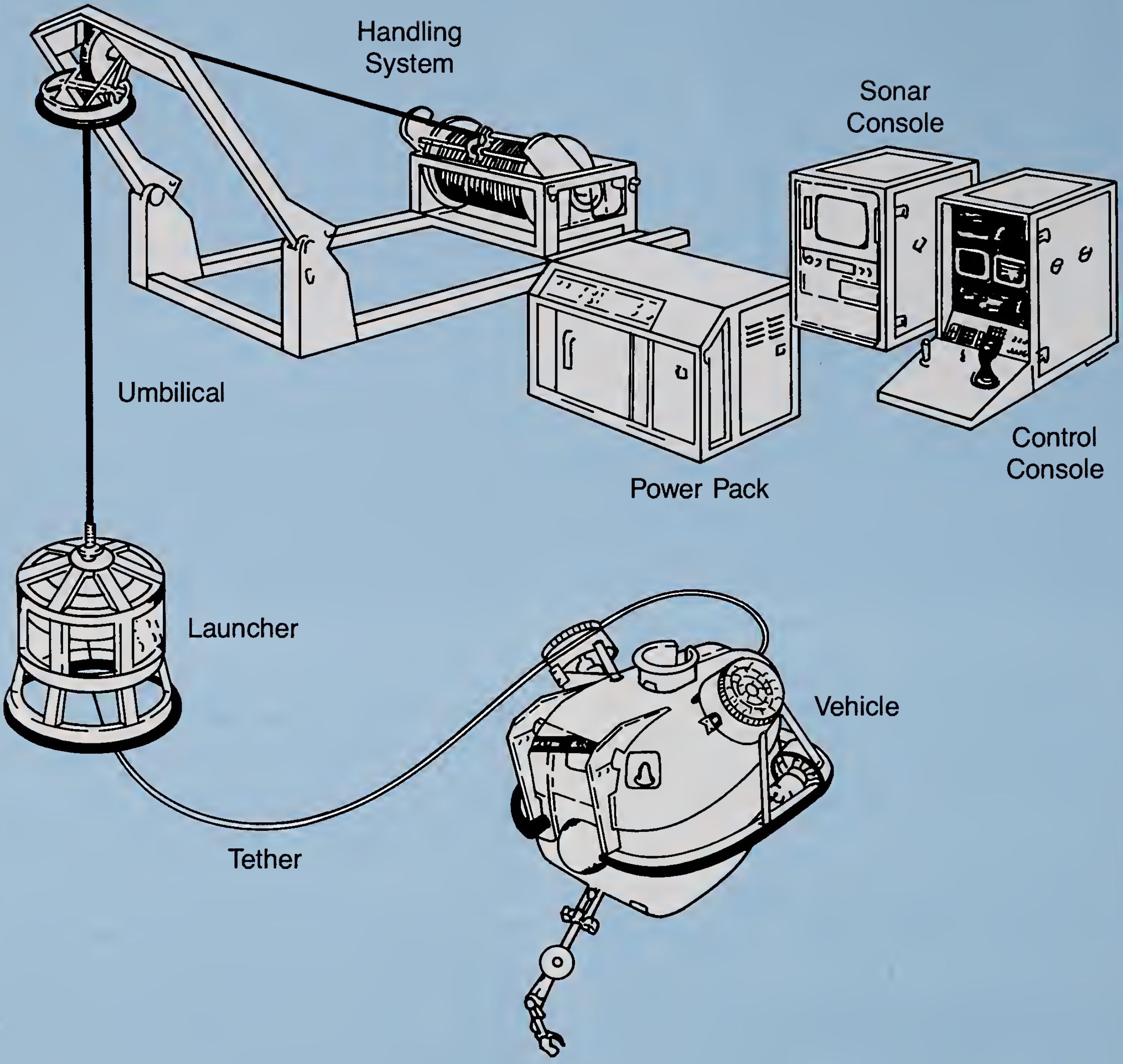
Monitor, Inspect, and Document Diver's Work

In the past, it has been difficult if not impossible for surface personnel to understand precisely what the diver is describing, what difficulties he or she is having, or, in the worst case, whether the work was performed properly. An ROV can be used to monitor the diver during work and to record task performance on video tape in real-time. This reduces communication problems and provides a permanent visual record that can be used to orient subsequent divers who may have to perform similar tasks. Many ROV's also carry still cameras that can be used to obtain high-resolution photographs.

WARNING

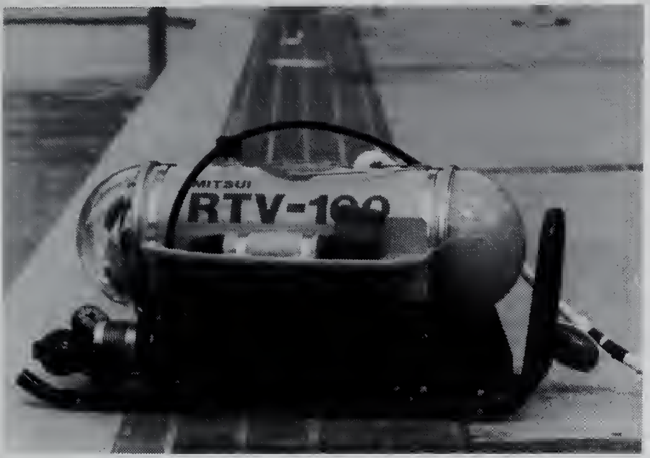
ROV's Used by Divers Must Be Safe Electrically and Mechanically—Propellers May Need Guarding and Some Form of Communication Should Be Established Between the ROV Operator and the Diver

Figure 17-19
ROV System Components



Courtesy Hydro Products, San Diego, CA

Figure 17-20
Mitsui Engineering and Shipbuilding RTV-100



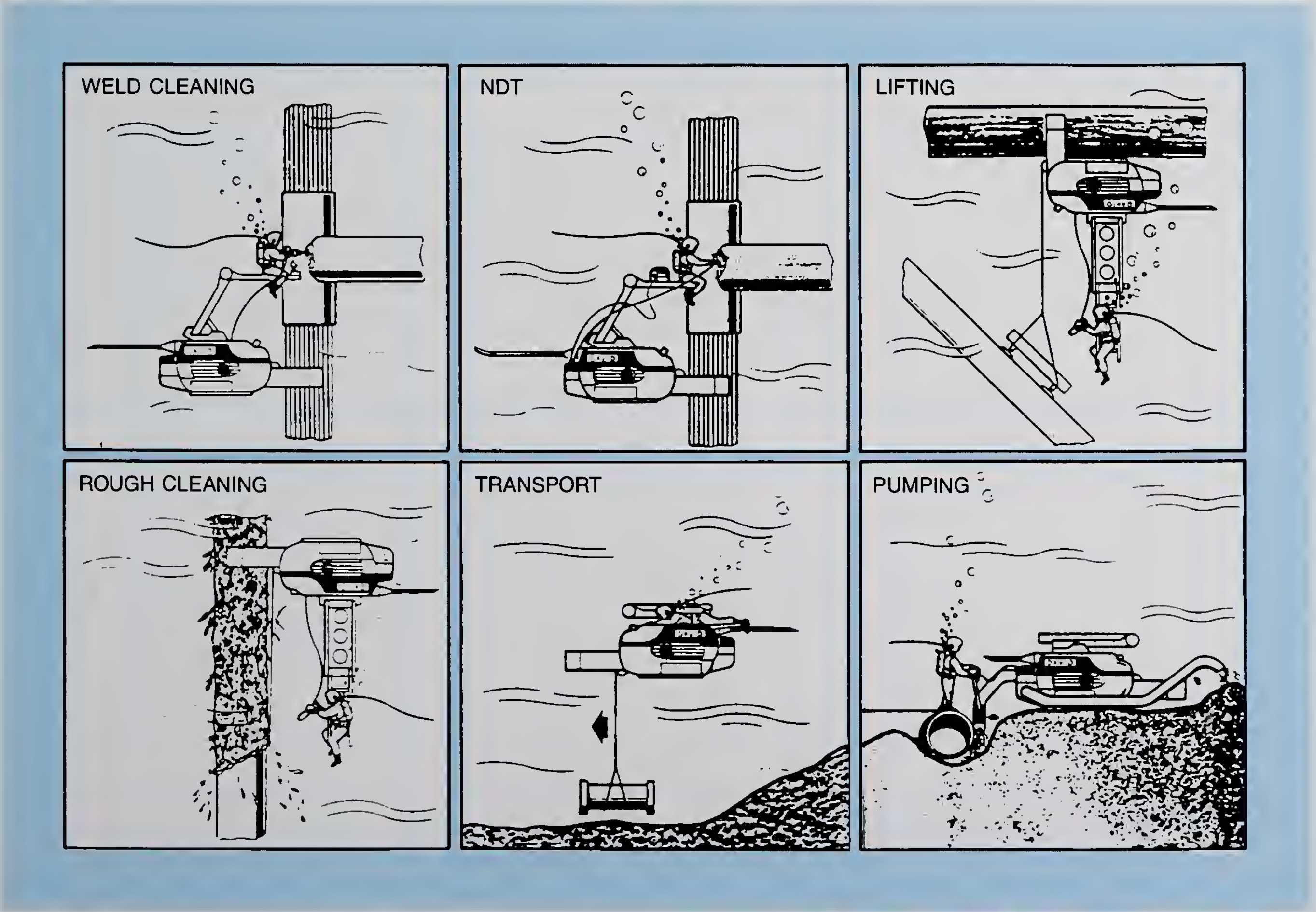
Courtesy Busby Associates, Inc.

Provide Lighting and Tooling Assistance

All ROV's have lights that can be used to provide additional illumination for divers. Although divers can carry flashlights, this practice leaves them with only a single hand free for work; if the light is head mounted, it may not adequately illuminate some angles that would make the task easier. The maneuverability of the smaller ROV's provides a variety of angles of attack.

The foregoing tasks have been performed by ROV's that were not specifically designed to provide for diver assistance. In 1984, the ROV *David* (Diver Assistance Vehicle for Inspection Duty) (Figure 17-21) completed sea trials and became available for work in underwater inspection, maintenance, and repair tasks. *David* is a large ROV that weighs more than 4 tons in air and measures 12.5 feet x 6.5 feet x 5.2 feet (3.8 meters x 2.0 meters x 1.6 meters). It can be controlled remotely from the surface or by the diver under water. The vehicle is equipped with a power winch, a diver's work platform, standard tools that include a grinder, cut-off saw, impact wrench, chipping hammer, hammer drill, and suction pump. It also carries three adjustable TV cameras and can provide the capability for water jetting and pumping equipment.

Figure 17-21
Examples of ROV David Work Tasks



Courtesy ZF-Herion-Systemtechnik GmbH, Fellbach, West Germany

SECTION 18 EMERGENCY MEDICAL CARE

EMERGENCY MEDICAL CARE 18

18.0 GENERAL

First aid is the immediate, temporary assistance provided to a victim of injury or illness before the services of a qualified physician-paramedical team can be obtained. The purpose of first aid is to save the victim's life and to prevent further injury or worsening of the victim's condition. When an accident occurs, the proper response can mean the difference between life or death, temporary or permanent disability, and short- or long-term hospitalization. Because diving is often conducted in isolated areas, all individuals involved in diving operations should have a thorough understanding of the basics of first aid and should complete, as a minimum, both the Advanced First Aid and Emergency Care and the Cardiopulmonary Resuscitation (CPR) courses offered or certified by the American Red Cross and the American Heart Association.

18.1 BASIC PRINCIPLES OF FIRST AID

The first step in administering first aid is to evaluate the victim's condition quickly and accurately and to elect an appropriate course of action. This evaluation must be done systematically, speedily, and comprehensively. Four phases are involved in the initial care of accident victims or victims of sudden medical problems; only the first three of these are considered first aid:

- Primary survey. This is a quick examination whose purpose is to identify and assess any life- or limb-threatening problems.
- Resuscitation phase. In this phase, life-threatening conditions are treated. This phase and the primary survey can sometimes, depending on the situation, be accomplished simultaneously.
- Secondary survey. This is a head-to-toe evaluation of the patient and includes x ray and other laboratory studies. Although best performed in an emergency room, the secondary survey phase of first aid should include the identification of less serious injuries, because treatment may be necessary to prevent further injury.
- Definitive care. During this phase, the patient's major problems are corrected and less threatening problems are dealt with. Because this phase is not part of first aid, it will not be discussed further in this section.

The following paragraphs provide more detailed discussions of the three first aid phases.

18.1.1 Primary Survey

The first priority in any first aid situation is to make sure that the patient can breathe, has a heart beat, and is not obviously hemorrhaging to death. The primary survey covers the ABC's of initial first aid, which are:

A. Airway maintenance and cervical spine control
B. Breathing
C. Circulation and hemorrhage control.

A decision tree depicting the sequence for this survey is shown in Figure 18-1.

18.1.1.1 Airway Maintenance and Cervical Spine Control Survey

The first step is to make sure that the patient's airway is open. This can be done by applying the chin lift or jaw thrust maneuver or by clearing the airway of debris with the fingers (see Section 18.2.1 for techniques). It is important to remember when establishing an airway that the patient may have a cervical spine injury that may be made worse during maneuvers to establish an airway. The patient's head and neck should never be hyperextended to establish or maintain an airway.

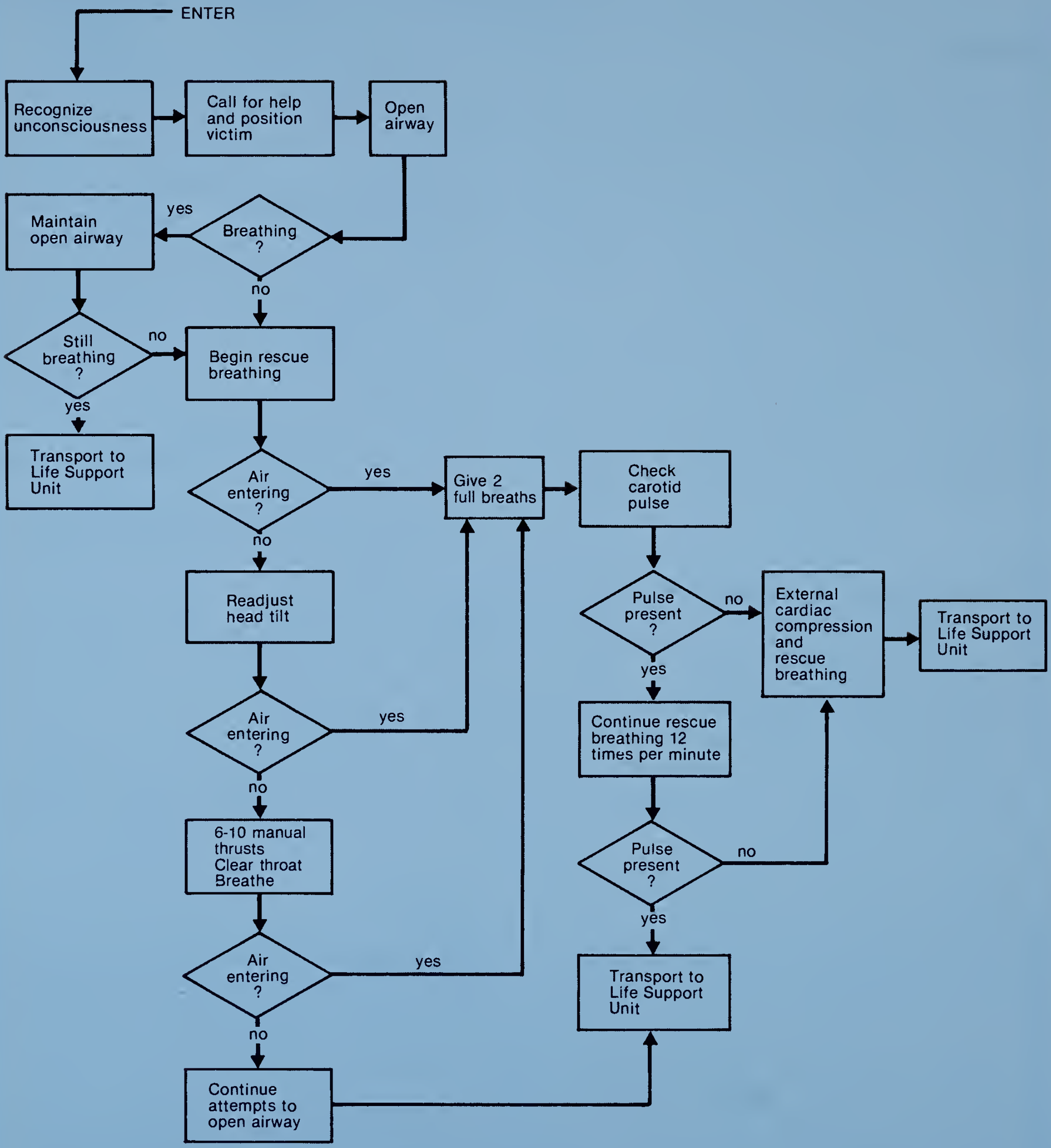
WARNING

If There Is Any Obvious Injury Above the Clavicles, the Person Administering First Aid Should Assume That a Cervical Spine Fracture Exists

18.1.1.2 Breathing Survey

The establishment of an adequate airway does not ensure that the victim has adequate respiration. The victim's chest should be exposed to observe if there are any obvious injuries and to see whether both sides of the chest rise and fall together. If the victim is not breathing, cardiopulmonary resuscitation must be instituted.

Figure 18-1
Life-Support Decision Tree



Source: JAMA (1986)

18.1.1.3 Circulation and Hemorrhage Control Survey

The person administering first aid should feel for a pulse to determine if cardiac arrest has occurred. The easiest place to find a pulse is over the carotid artery in the neck. If there is no pulse, CPR must be instituted. Rapid blood loss should be identified during the initial survey and managed by the direct pressure method (see Section 18.5).

18.2 AIRWAY MAINTENANCE AND CERVICAL SPINE CONTROL

The first step in determining whether a victim has an airway obstruction is to:

LOOK for breathing movements;
LISTEN for airflow at the mouth and nose; and
FEEL for air exchange.

The person administering first aid should not be misled into thinking that a victim is breathing adequately because his or her chest is rising and falling in the usual manner, because involuntary muscle action may cause the chest to continue to move even when the airway is completely obstructed. It is important to remove any gear and to open the wet suit jacket or cut it away so that the victim's chest can be seen and felt.

Unless the exchange of air through the mouth and nose can be heard or felt and it is possible to see that the victim's chest is rising and falling, the person administering first aid should not assume that the victim is breathing adequately. To hear and feel the exchange of air, the person conducting the survey should place his or her ear close to the patient's mouth and nose; in cases of complete obstruction, there will be no detectable movement of air. However, partial obstruction is easier to detect and can be identified by listening. Noisy breathing is a sign of partial obstruction of the air passages. 'Snoring' usually indicates obstruction by the tongue, which occurs, for example, when the neck is flexed. 'Crowing' can indicate spasms of the larynx, while gurgling sounds can indicate that foreign matter has lodged in the larynx or trachea. Under no circumstances should noisy breathing go untreated.

Cyanosis, or a noticeable dusky bluish coloration of the lips, nailbeds, or skin, is not a reliable sign of airway obstruction, particularly in a diver who is cold. The presence or absence of cyanosis should not be used to judge the adequacy of the victim's airway or of his or her breathing.

18.2.1 Establishing the Airway

If the patient is unconscious, one of two maneuvers can be used to open the airway and maintain it. The first, called the chin lift, is done by placing the fingers of one hand under the front of the chin and gently lifting the chin upward. The thumb of the same hand is used to depress the lower lip and open the mouth. The thumb may also be placed behind the lower teeth to lift the chin gently. This maneuver should not hyperextend the head, and it is the method of choice if a cervical spine injury is suspected because it does not risk compromising a possible cervical spine fracture and converting a fracture without cord injury into one with cord injury. The second maneuver is performed by grasping the angles of the lower jaw and pulling the jaw upward and forward. The lower lip may be pulled down with the thumbs (Figure 18-2).

After performing either of these maneuvers, the person administering first aid should check the mouth to see if any foreign matter, blood, or vomitus is blocking the airway. Any foreign matter should be removed by inserting the index finger of one hand down alongside the cheek, moving it to the base of the tongue, and sweeping the finger across the back of the base of the tongue to the other side and out, bringing the obstructing material with it.

If the victim does not begin to breathe on his or her own immediately after this maneuver, it may be because an obstruction continues to exist lower in the respiratory tract. The rescuer should attempt to inflate the victim's chest by beginning cardiopulmonary resuscitation. If the rescuer cannot force air into the lungs, the following methods can be used to dislodge an obstruction.

Manual Thrusts

Manual thrusts consist of a rapid series of 6 to 10 thrusts to the upper abdomen (abdominal thrust) or lower chest (chest thrust) that are designed to force air out of the victim's lungs.

Abdominal Thrusts (Heimlich Maneuver)

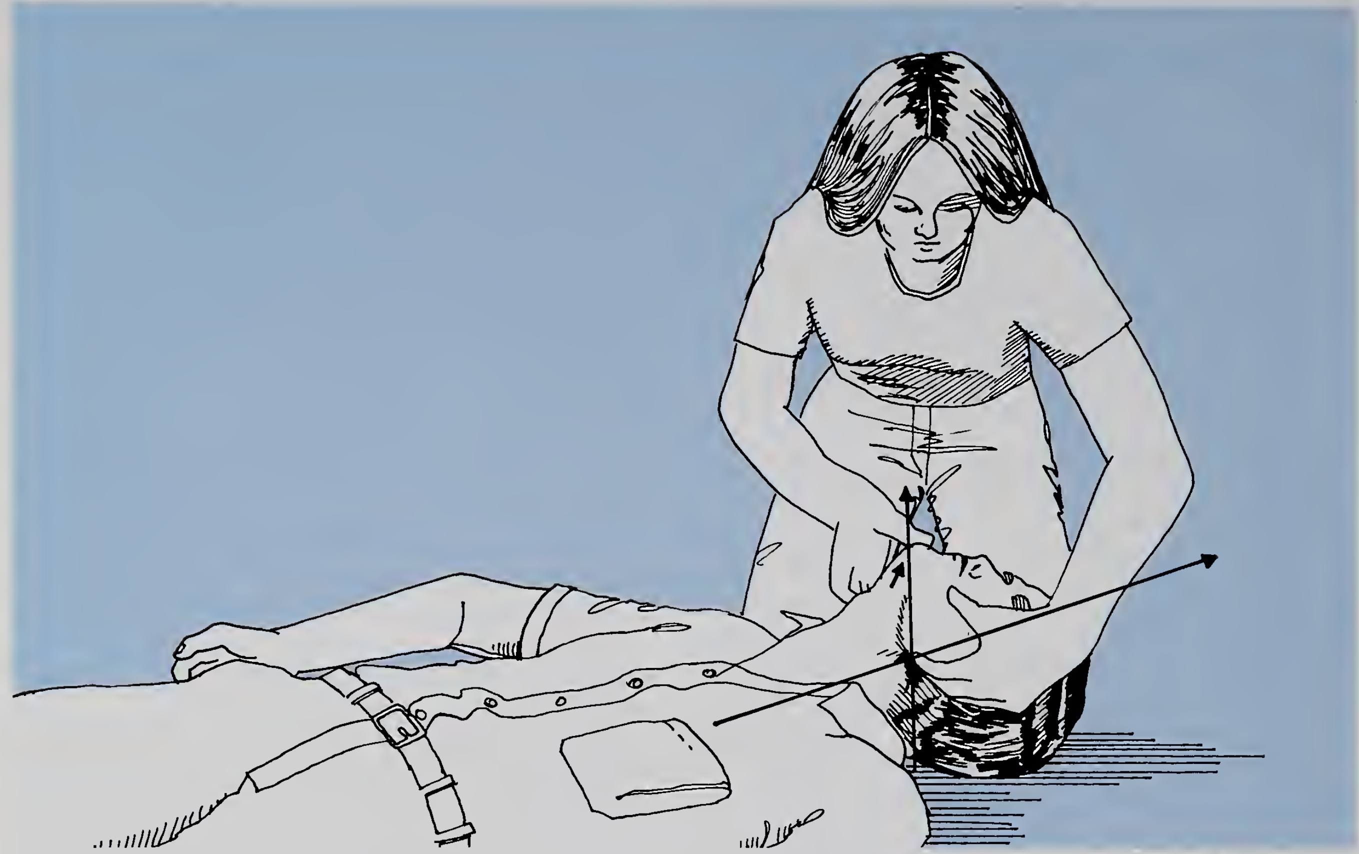
Victim Standing or Sitting

- The rescuer should stand behind the victim and wrap his or her arms around the victim's waist.
- The rescuer should grasp his or her fist with the other hand and then place the thumb side of the fist against the victim's abdomen, between the lower end of the victim's breastbone and the victim's navel.
- The rescuer should press his or her fist 6 to 10 times into the victim's abdomen with a quick upward thrust.

Victim Lying

- The rescuer should position the victim on his or her back, with the rescuer's knees close to the

Figure 18-2
Jaw-Lift Method



Source: NOAA (1979)

victim's hips, and should then open the victim's airway and turn the victim's head to one side.

- The rescuer should place the heel of one hand against the victim's abdomen, between the lower end of the victim's breastbone and the victim's navel, and should then place the second hand on top of the first hand.
- The rescuer should move sharply forward until his or her shoulders are directly over the victim's abdomen, which puts pressure on the victim's abdomen. This should be repeated 6 to 10 times.

Chest Thrusts

This technique is an alternative to the abdominal thrust. It is particularly useful when the victim's abdominal girth is so large that the rescuer cannot fully wrap his or her arms around the victim's abdomen, or when pressure applied directly to the victim's abdomen is likely to cause complications, as would occur, for example, if the victim were in advanced pregnancy.

Victim Standing or Sitting

- The rescuer should stand behind the victim, place his or her arms directly under the victim's armpits, and encircle the victim's chest.
- The rescuer should place the thumb side of his or her fist on the victim's breastbone, but not on the lower end of it or on the margins of the victim's rib cage.
- The rescuer should then grasp his or her fist with the other hand and exert 6 to 10 quick backward thrusts.

Victim Lying

- The rescuer should place the victim on his or her back and kneel close to the side of the victim's body. The rescuer should open the victim's airway and turn the victim's head to one side.
- The rescuer's hand position for and application of chest thrusts are the same as those for applying closed-chest heart compression (heel of rescuer's hand on lower half of victim's breastbone).
- The rescuer should then exert 6 to 10 quick downward thrusts that will compress the victim's chest cavity.

Conscious Victim

If the victim has good air exchange, only partial obstruction, and is still able to speak or cough effectively, the rescuer should not interfere with the victim's attempts to expel a foreign body. The following sequence of maneuvers (described in detail below) should be performed by the rescuer if there is airway obstruction:

- Determine if the airway obstruction is complete by asking the victim to speak.
- Deliver 6 to 10 manual thrusts.
- Repeat 6 to 10 manual thrusts until they are effective or until the victim loses consciousness.

18.2.2 Cervical Spine Control

Cervical spine injury should be suspected if there is evidence of any injury above the clavicles. The absence of neurological signs or the presence of reflexes should not be considered evidence that no cervical spine injury exists; only an x ray can rule out such an injury.

The management of a suspected cervical spine injury is immobilization of the head and neck. This can be done with sand or sandbags, weights, rocks, or anything that is heavy enough to keep the head from moving. If another person is present, immobilization can be accomplished by having the other person hold the victim's head on both sides and apply slight traction to the head. If a patient must be rolled on the side because of vomiting or severe bleeding that is obstructing the airway, this can be done if no back board or cervical brace is available by moving the body and head together while maintaining their relative positions. This is extremely difficult to do because of the weight of the head, which must be held and rolled with the body while the helper continues to apply traction. As emphasized in the previous section, the cervical spine should not be extended during the establishment of an airway if cervical spine injury is suspected.

18.3 BREATHING (MOUTH-TO-MOUTH OR BAG-VALVE-MASK RESUSCITATION)

If, after establishing an airway, the victim does not begin breathing on his or her own, the rescuer should begin resuscitation efforts, which may require both cardiac and respiratory resuscitation. This section deals with the procedure for providing respiration to a victim.

18.3.1 Mouth-to-Mouth Resuscitation

If the airway is being maintained by using the chin lift method, the rescuer should pinch the victim's nostrils closed with the hand that is not holding the victim's chin, make a seal with his or her mouth over the victim's mouth, and exhale into the victim's mouth. The rescuer then removes his or her mouth and turns the face away while the victim exhales. When exhaling into the victim, the rescuer should make sure that the victim's chest rises, which is proof that the victim's airway is open. If it is not, the rescuer should recheck whether the victim's jaw is lifted fully, the tongue is held out of the way, etc. The rescuer should give the victim two full breaths and check for a carotid pulse. If a pulse is present, the rescuer should continue with mouth-to-mouth breathing at the rate of 10-12 breaths per minute until the victim begins breathing on his or her own or until the rescuer is relieved by someone else or is too exhausted to continue. If a pulse is not present, the rescuer should begin combined cardiopulmonary and respiratory resuscitation, which is described in Section 18.4.

If a rescuer is using the two-hand jaw-lift method to maintain the victim's airway, the rescuer can seal the victim's nostrils by pressing his or her cheek against them. In some cases, the victim's jaw may be badly damaged or the victim's mouth cannot be forced open. If this happens, a rescuer can perform resuscitation by sealing the victim's mouth and exhaling into the victim's nose.

18.3.2 Bag-Valve-Mask Resuscitation

If a bag-valve-mask resuscitator (BVMR) (Figure 18-3) and a trained user are available, this device should be used to treat cardiac arrest. The self-inflating bag-valve-mask forms an airtight seal around the victim's mouth and nose. It can deliver a higher partial pressure of oxygen than is possible with mouth-to-mouth resuscitation, and the resuscitator can be used in atmospheric air, which contains 21 percent oxygen compared with the 16-17 percent in the exhaled air of a rescuer. A BVMR can also be supplied with 100 percent oxygen. In addition, rescuers using a BVMR can ensure that the victim is ventilating adequately and can detect and correct airway obstruction.

NOTE

A bag-valve-mask resuscitator should be used only by those who are trained and proficient in its use.

Precautions

- An oropharyngeal airway should be inserted in an unconscious victim only if the rescuer is trained in this procedure.
- Bag-valve-mask resuscitators should not be used on children younger than 2 years.

Figure 18-3
Bag-Valve-Mask Resuscitator

A. Complete System

B. Operating Position

Source: NOAA (1979)

- Rescuers should ensure that the face mask is completely sealed about the victim's nose and mouth.
- Rescuers should never use oxygen flow rates that are in excess of 10 liters per minute.
- Rescuers should always release the bag quickly and completely.

While maintaining the victim's airway, the rescuer should apply the mask firmly to the victim's face, with the rounded cushion between the victim's lower lip and chin and the narrow cushion as high on the bridge of the victim's nose as possible. The rescuer should hold the mask firmly against the victim's face with the thumb and index finger while keeping the victim's chin and head tilted back with the other three fingers. The rescuer should ensure that there is an airtight seal between the mask and the victim's face. The rescuer should then squeeze the bag firmly while observing the victim's chest for rise. When administering air to a child, the rescuer should exercise care not to overexpand the child's lungs. The rescuer should release the bag sharply and completely to allow the victim to exhale (observe for chest fall) and then repeat this squeeze-and-release pattern approximately every 3 to 4 seconds (about 1 second for chest rise and 2 seconds for chest fall). The rescuer should continue resuscitation until he or she is too exhausted to continue or until additional qualified help comes.

If oxygen is available, the rescuer can use the procedures described above, except that an oxygen bottle should be connected to the bag-mask system and the oxygen should be allowed to flow at a rate of 8-10 liters per minute.

When using this method, the rescuer should be alert for signs of vomiting. If vomiting occurs, quickly remove the mask, turn the victim's head to one side, and clean out the victim's mouth. After the vomiting has stopped and the mouth has been cleared, the rescuer should resume resuscitation.

18.4 CIRCULATION

This section describes the procedure for performing CPR if no pulse is found in a non-breathing victim.

18.4.1 Treatment by One Person

The rescuer should give the victim two full rapid mouth-to-mouth ventilations; then, with the heel of one hand on the lower third of the victim's breastbone and the other hand directly on top of that hand, the rescuer should press vertically downward about 1.5 inches (3.8 centimeters). The rescuer should then release the pressure contact with the victim's chest. This downward pressure should be applied 15 times, at the rate of 80 per minute, after which the victim should be ventilated twice. This two-ventilation procedure should be repeated after every 15 heart compressions, until the pulse or spontaneous respiration (or both) returns, the victim is pronounced dead by a physician, or the rescuer cannot continue because of exhaustion.

18.4.2 Treatment by Two People

With the heel of one hand on the lower third of the victim's breastbone and the other hand directly on top, the rescuer should press vertically downward, using some body weight, until the victim's breastbone depresses about 1.5 to 2 inches (3.8 to 5.1 centimeters). While maintaining contact with the victim's chest, the rescuer should then release the pressure by lifting his or her hands. This pressure should be applied at the rate of 60 times per minute. Simultaneously, a second person should apply mouth-to-mouth resuscitation at the rate of one ventilation for each five pressure applications to the heart, without a pause in the pressure applications. To determine whether the pulse has returned, it should be checked every four cycles.

This routine should be continued until a pulse or spontaneous respiration returns, the rescuer(s) is exhausted, or the victim is pronounced dead by a physician. If the victim's heart begins beating and the victim breathes on his or her own, close observation must be continued until medical help arrives because respiratory or cardiac arrest may suddenly recur.

18.5 BLEEDING

If a diver suffers an injury under water, the rescuer's first action should be to remove him or her from the water. The first step in stopping severe hemorrhaging is for the rescuer to apply direct pressure on the wound, which can be done using the hand, finger, or a sterile dressing. The most sterile material available should be used, although time should not be wasted looking for something sterile. The victim should be lying down and, unless the injury prevents this, the injured area should be elevated higher than the heart. Pressure should be maintained for no less than 10 minutes. The rescuer should cover the entire wound, if possible, with the fingers or palm of the hand. If blood seeps through the covering, the rescuer should not remove it but should add more material and continue to apply pressure. This method of controlling bleeding is much more effective than using either pressure points (places where major arteries lie close to the skin) or tourniquets.

A tourniquet is a constricting band used as a last resort to stop serious bleeding in a limb. A traumatic amputation, crushed limb, or cases in which direct pressure fails to stop the bleeding are instances in which a tourniquet should be used. In these situations, a wide belt or strong piece of cloth not less than 2 inches (5.1 centimeters) wide should be tied around the victim's injured limb above the wound, using an overhand knot. A short stick is tied to the band at the overhand knot, and the tourniquet is tightened by rotating the stick. The tourniquet should only be as tight as necessary to stop the bleeding. Once in place, the tourniquet should be loosened only on the advice of a qualified physician. A tag should be placed on the tourniquet indicating at what time it was applied. Before applying it, one last effort should be made to stop the bleeding by using direct pressure.

18.6 SHOCK

Shock may occur after any trauma and will almost always be present to some degree when a serious injury occurs. Shock is caused by the loss of circulating blood, which causes a drop in blood pressure and decreased circulation. The resulting tissue hypoxia or anoxia can have permanent effects or may cause death.

Symptoms and Signs

- Feeling 'faint,' weak
- Agitation, mental confusion
- Unconsciousness
- Pale, wet, clammy, cold skin (not a reliable sign in a diver who has been in the water)
- Nausea, vomiting
- Thirst
- Rapid pulse; absence of peripheral pulses
- Systolic blood pressure 90 mmHg or less.

Treatment

The treatment of shock takes priority over all other emergency care measures except for the correction of breathing problems, the re-establishment of circulation, and the control of profuse bleeding. After respiration and cardiac output have been established and the control of bleeding has been instituted, the following procedures should be performed to treat shock.

- Administer 100 percent oxygen (if available) either by mask or, if the patient does not tolerate the mask, by allowing oxygen to free flow across the victim's nose from the end of the connector tubing.
- Elevate the lower extremities. Since blood flow to the heart and brain may have been diminished, circulation can be improved by raising the legs slightly (10-15 degrees). The entire body should not be tilted down at the head because the abdominal organs pressing against the diaphragm may interfere with respiration. If the legs are severely injured or fractures are suspected, the rescuer should not attempt leg elevation.
- Avoid rough handling. The victim should be handled as gently and as little as possible. Moving a victim has a tendency to aggravate shock conditions.
- Prevent loss of body heat. Keep the victim warm but guard against overheating, which can aggravate shock. The rescuer should remember to place

a blanket under the patient as well as on top, to prevent loss of body heat into the ground.

- Keep the victim lying down. This practice avoids taxing the victim's circulatory system at a time when it should be at rest.
- Give nothing by mouth.

18.7 NEAR-DROWNING

Near-drowning refers to an accident in which an apparently drowned and lifeless victim is pulled from the water and resuscitated. The causes of near-drowning are many but a frequent cause is diver panic, which incapacitates the victim and prevents him or her from surfacing or staying on the surface. As a result, the near-drowning victim inhales water or experiences a laryngeal spasm, which, in turn, causes severe hypoxia.

Symptoms and Signs

- Unconsciousness
- Lack of respiration
- Lack of heart beat.

Treatment

Immediate institution of cardiopulmonary resuscitation (see Section 18.4) is required in cases of near-drowning, even if the victim has been in the water for a long time. Cases of successful resuscitation have been reported even after 40 minutes of submersion, presumably because the rapid hypothermia associated with immersion in cold water protects the brain and other vital organs from permanent injury. If hypothermia is suspected, see Section 18.8.3 for other procedures that should be performed in addition to CPR.

WARNING

Do Not Withhold CPR Because a Drowning Victim Appears to be Dead. The Victim May Only Appear to be Dead Because of Severe Hypothermia

18.8 HEAT AND COLD CASUALTIES

18.8.1 Heat Exhaustion

Heat exhaustion occurs when cardiac output and vasomotor control cannot meet the increased circulatory demands of the skin in addition to those of the brain and muscles. It is caused by simultaneous exposure to heat and very hard work in a hot, humid environment. Where heat exhaustion is likely, periodic rest breaks should be taken in the shade or other cool place. Fluid intake should be forced, even when not thirsty, because thirstiness is a poor indicator of dehydration.

Symptoms and Signs

- Rapid weak pulse
- Nausea, vomiting
- Fainting
- Restlessness
- Headache
- Dizziness
- Rapid, usually shallow, breathing
- Cold, clammy skin, continuous sweating.

Treatment

The victim of heat exhaustion should be placed in a shaded, cool place in a comfortable position, either lying down or semi-reclining, and should be protected from chilling. The victim should be forced to drink a quart of any non-alcoholic fluid as soon as possible; this drink does not need to be iced. The victim should recover fairly rapidly, but symptoms such as headache and exhaustion may linger. Further heat exposure should not be allowed until all symptoms are gone.

18.8.2 Heatstroke

Heatstroke is a result of excessive physical exertion in a hot environment and is caused by failure of the body's thermoregulatory mechanism. It can be avoided by limiting exertion, wearing protective clothing, and preventing dehydration. Heatstroke is a serious emergency, and the body temperature of a heat stroke victim must be lowered quickly to prevent permanent brain damage or even death.

Symptoms and Signs

- Rise in body temperature
- Sudden collapse
- Skin extremely dry and hot, no sweating
- Dizziness
- Mental confusion
- Convulsions
- Coma.

Treatment

The major factor in treating heatstroke is to lower the body temperature to a safe level as quickly as possible. The victim's body should be bathed in tepid water or, if possible, completely immersed. The head and neck of the victim should be sponged with the same tepid water. If conscious, the victim should drink large amounts of any non-alcoholic fluid. Transfer to a medical facility should be accomplished immediately; without proper medical care, serious complications are possible.

18.8.3 Hypothermia

Strictly defined, hypothermia is a decrease in the body's core temperature to a level below 98.6°F (37°C). However, many people can stand a drop in core temperature of 0.9°F (0.5°C) without significant problems. If the temperature continues to drop, shivering begins and becomes uncontrollable. A core temperature of 91.4°F (33°C) is lethal for about 50 percent of all victims of such hypothermic exposure. The symptoms and signs of hypothermia are many and are listed below in the order of their appearance with decreasing core temperature.

Symptoms and Signs

- Cold skin and vasoconstriction
- Sporadic shivering
- Uncontrollable shivering
- Mental confusion, impairment of rational thought
- Loss of shivering response
- Sensory and motor degradation
- Hallucinations, decreasing consciousness
- Cardiac abnormalities
- Loss of consciousness
- Loss of reflexes
- Ventricular fibrillation and death.

If a hypothermic victim is conscious and can help himself or herself, no vigorous rewarming procedures should be attempted. Warm dry clothing, hot soup, tea, or coffee, and the avoidance of further cold exposure are recommended. If spontaneous respiration is present but the victim is still unconscious or extremely lethargic, active rewarming should be instituted.

Active rewarming should be done at a medical facility, but simple steps, such as body-to-body rewarming, can be taken at the dive site while waiting for medical evacuation. If a supply of hot water is available, run warm water, 102 to 109°F (39 to 43°C) into the victim's diving suit with a hose. Further heat loss should be prevented by shielding the victim from the wind to block the evaporative cooling of wet skin and clothes. Mouth-to-mouth resuscitation also reduces respiratory heat loss but should be administered only if the victim is not breathing spontaneously. Providing warmed, saturated air or oxygen at 104 to 113°F (40 to 45°C) prevents respiratory heat loss and adds a little heat to the body core.

The major means of rewarming involves immersion of the victim's body in warm water at 104 to 109°F (40 to 43°C) until his or her rectal temperature has climbed to 96.8°F (36°C) and the patient is again alert. Rewarming is best done in a medical facility, where the process can be closely monitored, because of the serious cardiac and metabolic problems that can occur during this process. However, rewarming in a habitat or a saturation chamber may be necessary if, for example, the victim cannot be taken to a hospital until he or she has been decompressed. Hot water should be introduced into the diving suit unless a hot tub is available in the chamber. Pulse rate and blood pressure should be taken frequently to guard against rewarming shock, which can occur as the patient rewarms. As peripheral blood vessels reopen, peripheral resistance is lowered and, if the cardiac output is low, hypotension can occur. Hydrostatic support, such as that provided by keeping the suit full of water or keeping the diver in the tub, can also be helpful.

18.9 INJURIES AND INFECTIONS

18.9.1 Injuries to the Spine

Symptoms and Signs

- Local pain or tenderness over the vertebrae
- Painful movement of back or neck
- Deformity or an obvious hump (both are rare signs)
- Severe trauma to rest of body
- Paralysis or lack of sensation in a body part.

To check a conscious patient for spinal cord injury, rescuers should observe the following procedures:

- Ask the victim what happened, where it hurts, whether hands or feet can move, whether sensation is present in hands and feet
- Look for bruises, cuts, deformities
- Avoid moving the injured patient if the neck and spine cannot be immobilized.

For an unconscious patient, the rescue procedures to be observed are:

- Look for trauma or deformities
- Ask others what happened
- Avoid moving the patient if spinal injury is suspected
- Provide resuscitation as required
- Report any symptoms or signs observed to the physician or rescue team.

18.9.2 Injuries to the Head and Neck

Symptoms and Signs

- Injury to the skull (including face)
- Blood or clear fluid (cerebrospinal fluid) draining from ears or nose

- Black eyes
- Unconsciousness
- Paralysis or loss of sensation
- Uneven dilation of pupils (one dilated more than the other)
- Airway obstruction.

Treatment

- Assume that a cervical spine injury is present
- Maintain respiration and circulation
- Control active bleeding.

The face and scalp are richly supplied with arteries and veins, and wounds of these areas bleed heavily. Bleeding should be controlled by direct pressure. For cheek wounds, it may be necessary to hold a gauze pad inside the cheek as well as outside. The main danger of facial fractures is that they can cause airway problems if bone fragments or blood obstructs the airway. If a neck wound is present, a neck fracture should be suspected and the victim's head and neck should be immobilized to prevent injury to the spinal cord.

18.9.3 Wounds

Divers can experience a wide variety of wounds. The majority, such as coral wounds or wounds from sharp edges of metal, are minor and require a minimum of first aid. However, there is always the chance that a diver will sustain massive injuries, such as might be inflicted by a shark or a boat propeller. In such cases, the right response, promptly applied, may be necessary to stop bleeding and prevent shock.

Minor wounds, abrasions, scratches, small lacerations, etc., may be noticed by a diver at the time they occur under water. When such wounds are noticed after the diver leaves the water, they should be washed gently with soap and water and covered with a sterile dressing.

If the wound is deep, gaping, or has a large flap of skin, the diver should immediately leave the water, rinse the wound with plain water, and cover it with a sterile dressing. Medical attention should be sought because wounds occurring under water are more liable to become infected than those occurring on the surface. Antibiotic ointments or other medications should not be introduced into open wounds because they will have to be removed from the wound before definitive care can be administered.

A rescuer's most immediate concern when confronted with a major wound is to stop the bleeding and prevent the onset of shock. Bleeding should be controlled with a pressure dressing (see Section 18.5). Steps should be taken to prevent shock until medical aid is obtained (see Section 18.6).

Objects that are impaled in the body or eye should not be removed except under direct medical supervision; instead, they should be stabilized for transport to medical care. The only exception to this rule occurs in the case of an object that penetrates the cheek. Such an object can be removed, after which the wound should be packed inside the mouth to prevent the victim from choking on blood.

18.9.4 Burns

Burns are classified into three general categories, according to severity. The least serious is the first-degree burn, which is a reddening of the skin. With second-degree burns, the skin is blistered. The most serious is the third-degree burn, in which the skin (and possibly the underlying tissue) is charred beyond repair. Burns can result from either heat or chemical action.

Treatment

The treatment that can be administered to a burn victim other than by a physician is extremely limited. The immediate treatment for all burns, however, is immersion in cool or tepid water to reduce tissue temperatures rapidly to levels below those that cause damage. If the skin is broken or burned through, the burned area itself should be covered with a sterile or clean dressing, using a material that will not adhere to the burn, to exclude air from the area. (Blisters should not be opened.)

In minor burn cases, the victim may be given aspirin to reduce the pain. To assist in replacing lost fluids, the victim may be given liquids, except alcohol. All burns of more than a minor degree may be accompanied by shock, and the victim must be observed carefully and treated accordingly. For all burns except minor reddening of the skin, the victim should be examined by a doctor. Burn ointment, grease, baking soda, or other substances should not be applied to burns that involve opened blisters or other wounds.

Sunburn is common for anyone who spends time near the water. Avoiding prolonged, direct exposure to sunlight and wearing protective clothing and sunshield ointment are the best sunburn prevention. A sunshield with a protection factor of 15 should provide good protection if used properly. Sunshields with lower protection factors provide correspondingly lower shielding capabilities. Sunburns can cause skin damage severe enough to keep the sunburned individual from working.

Symptoms and Signs

- Prickly sensation on skin in affected area
- Pain and tenderness to the touch
- Extreme redness
- Blisters
- A desire to avoid having the affected area come into contact with clothing
- Fever.

Treatment

Many sunburn ointments that provide partial relief are commercially available. If no special ointment is available, bandages soaked in cool water will provide some relief. The victim should avoid further exposure until the condition has passed. Sunburn blisters should not be opened.

18.10 FRACTURES

It is unusual for a diver to suffer a fracture while diving. Diving-related fractures usually occur on the surface. If divers suffer fractures while submerged, they should immediately terminate the dive.

Fractures can be classed into two general types. A closed fracture consists of a broken bone that has not penetrated the skin. In an open (compound) fracture, the broken bone has caused an open wound, from which the bone frequently protrudes. This type of wound is complicated by the likelihood of infection.

Symptoms and Signs

- Area of fracture painful and tender
- Inability to move affected limb
- Limb bent at unusual angle
- Swelling in area of fracture
- Abnormal movement occurring at a location other than a joint.

Treatment

The only first aid required for closed fractures is to immobilize the affected limb with a splint. Flat pieces of wood, plastic, metal, or any firm substance may be used. Inflatable splints are excellent. The splint serves to prevent movement and consequent complication of the injury. To prevent movement, the splint should be bound to the limb at a minimum of three places: at the wound, and above and below the joints closest to the fracture.

When treating an open fracture, the limb should not be moved to its natural position. The open wound should be covered with a sterile dressing and splinted to prevent movement. With any fracture, shock should be anticipated and its symptoms treated (see Section 18.6). Regardless of the type of fracture, the rescuer should not try to set the bone; this should be done only by qualified medical personnel. In joint injuries (shoulder, elbow, wrist, knee, or ankle), the injury should be immobilized just as it was found; moving the joint may damage nerves or major blood vessels.

18.11 ELECTROCUTION

Electrocution may result from the careless handling, poor design, or poor maintenance of power equipment, such as welding and cutting equipment or electric underwater lights. All electrical equipment used under water should be well insulated. In addition, divers should be properly insulated from any possible source of electrical current.

When leaving the water to enter a boat or habitat, divers should not carry a connected light or electric tool. Victims may not be able to separate themselves from the source of the shock.

Signs

- Unconsciousness
- Cessation of breathing
- Cardiac arrest
- Localized burns.

Treatment

The first step in treatment is to neutralize the source of electricity to protect the rescuer and the victim. If this cannot be done immediately, a non-conductive substance (such as a piece of lumber) should be used to break the contact between the source and the victim. The victim must then be treated for cardiac arrest and given artificial resuscitation, if necessary (see Section 18.4). Regardless of how complete the recovery may seem, the victim should be examined by a physician immediately because of the possibility of delayed cardiac or kidney complications.

18.12 SEASICKNESS (MOTION SICKNESS)

Seasickness can be a distinct hazard to a diver using small craft as a surface-support platform. Diving should *not* be attempted when a diver is seasick: vomiting while submerged can cause respiratory obstruction and death.

Symptoms and Signs

- Nausea
- Dizziness
- Feelings of withdrawal, fatigue
- Pallid or sickly complexion
- Slurred speech
- Vomiting.

Prevention

There is no effective treatment for seasickness except to return the stricken diver to a stable platform. All efforts are therefore directed at prevention. Some people are more susceptible than others, but repeated exposures tend to decrease sensitivity. Suggestion therapy by a trained mental health specialist has been helpful in some cases. The susceptible person should eat lightly just before exposure and avoid diving with an alcohol hangover. Seasick individuals should be isolated to avoid affecting others on board adversely. Drug therapy is of questionable value and must be used with caution because most motion sickness preparations contain antihistamines that make the diver drowsy and could affect a diver's judgment. The administration of scopolamine by means of a skin patch has been shown to be useful in preventing seasickness, but this drug may cause psychotic behavior in sensitive persons. Drugs should be used only under the direction of a physician who understands diving, and then only after a test dose on non-diving days has been shown not to affect the individual adversely.

18.13 POISONING CAUSED BY MARINE ANIMAL ENVENOMATION

18.13.1 Envenomation Caused by Fish

Divers are in contact with a variety of marine life that can inflict poisonous wounds if handled carelessly. Some of the most frequently encountered wounds are inflicted by stingrays, stonefish, scorpionfish, catfish, and sea urchins. (For more detailed information on the identification of poisonous marine animals, see Section 12.) The poisoning caused by these animals ranges from mild to fatal, depending on the animal, wound site, amount of poison injected, and individual susceptibility.

Symptoms and Signs

- Severe, localized pain at the wound site
- Localized swelling, which may be accompanied by an ashy appearance
- Fainting, weakness, nausea, or shock
- Respiratory distress
- Cardiac arrhythmias, cardiac arrest.

Treatment

Because fainting is common after a poisonous wound, the victim should be removed from the water as soon as possible. The wound should be washed with a sterile saline solution or cold salt water. The wound should be soaked in water as hot as the victim can stand (not more than 120°F (50°C)) for a period of at least 30 minutes because this may neutralize the venom. The patient should be observed for signs of cardiac or respiratory arrest. Medical assistance should be obtained as quickly as possible.

18.13.2 Envenomation Caused by Jellyfish

Jellyfish poisoning ranges in severity from minor to fatal.

Symptoms and Signs

(These vary depending on species and extent of sting.)

- Pain ranging from a mild prickly sensation to an intense throbbing, shooting pain
- Reddening of the area (welts, blisters, swelling)
- Pieces of tentacle on affected area
- Cramps, nausea, vomiting
- Decreased touch and temperature sensation
- Severe backache
- Loss of speech
- Frothing at the mouth
- Constriction of the throat
- Respiratory difficulty
- Paralysis
- Delirium
- Convulsions
- Shock.

Treatment

A diver who has been stung by jellyfish should be removed from the water as quickly as possible. The rescuer should remove any tentacles, taking care not to come into contact with them himself or herself. The wound area should be rinsed with vinegar, sodium bicarbonate solution, or boric acid solution to prevent untriggered nematocysts from discharging. The area should not be rinsed with fresh water or rubbed with sand to remove any tentacles, because this will cause increased stinging. The victim should be kept lying down with feet elevated, and CPR should be administered if required. In serious cases, medical support may be required.

18.13.3 Envenomation Caused by Cone Shells

These animals have a very toxic poison that has caused death in as many as 25 percent of cases.

Symptoms and Signs

- Stinging or burning at wound site
- Numbness or tingling at wound that spreads to the rest of the body
- Muscular paralysis
- Difficulty in swallowing and speaking
- Respiratory distress.

Treatment

The patient should be removed from the water immediately and laid down. A loose constricting band such as an ace wrap or belt should be placed above the sting to prevent venous drainage from the wound but should not be tight enough to stop arterial flow. Loosen for 90 seconds every 10 minutes. Immediate medical attention should be sought. Careful observation is required in case of cardiac or respiratory failure. Be prepared to administer CPR.

18.13.4 Envenomation Caused by Sea Snakes

The most serious poisonous bite is that of the sea snake. These reptiles are closely allied to the cobra and have a highly toxic venom. A sea snake bite usually is small and may not even be noticed, and the onset of symptoms is often delayed for 1 hour or more.

Symptoms and Signs

- Generalized malaise, anxiety, or, possibly, a feeling of well-being
- Difficulty with speech and swallowing
- Vomiting
- Aching or pain on movement
- Weakness, progressing within 1 to 2 hours to an inability to move, beginning in the legs
- Muscle spasm
- Droopy eyelids
- Thirst, burning dryness of throat
- Shock
- Respiratory distress
- Fang marks (two small punctures approximately 1/2 inch (1.3 centimeters) apart) and, possibly, a fang left in the wound.

Treatment

The victim must remain quiet. If bitten on the arm or leg, a constricting bandage should be placed above the wound but should not be drawn so tightly as to interrupt arterial flow. The band should be periodically loosened, as described in Section 18.13.3. The victim should be transported immediately to the nearest medical facility for the antivenom treatments necessary to combat the poison. If possible, capture or kill the snake for identification purposes.

18.13.5 Envenomation Caused by Coral

Coral is common in most tropical waters. These tiny animals leave behind a hard, calcium-like skeleton, which is frequently razor sharp and capable of inflicting painful wounds. The wounds tend to be slow in healing, easily infected, and, if not treated, may become ulcerous. Some corals have stinging cells similar to those in a jellyfish and produce a sting that rapidly disappears but may leave red itchy welts.

Symptoms and Signs

- Itchy, red, swollen area or wound
- Lingering, infected wound
- Lacerations, bleeding.

Treatment

The wound should be washed with soap and water to remove bacteria and foreign matter. An antiseptic should then be used and the wound covered with a sterile dressing. Aspirin or other mild analgesics may be used if the wound is painful; if severe, medical attention should be sought.

18.13.6 Envenomation Caused by Sea Urchins

Most divers in marine waters are familiar with the sea urchin. The spines of these creatures can penetrate wet suits, and, being very brittle, can break off at the slightest touch.

Symptoms and Signs

- Immediate sharp, burning pain
- Redness and swelling
- Spines sticking out of skin or black dots where they have broken off
- Purpling of skin around place spines entered
- Numbness.

Treatment

Spines that can be grasped should be removed with tweezers. Spines that have broken off flush with the skin are nearly impossible to remove, and probing around with a needle will only break the spines into little pieces. Most of the spines will be dissolved by the body within a week; others may fester and can then be pushed out to the point where they can be removed with tweezers. Alternately immersing the affected area in hot and cold water may help dissolve the imbedded fragments.

18.14 POISONING CAUSED BY EATING FISH OR SHELLFISH

18.14.1 Ciguatera

Ciguatera poisoning is caused by eating fish containing a poison (ciguatoxin) whose origin is unknown but which is believed to come from a certain species of algae eaten by the fish. There is no way to distinguish fish with ciguatera from harmless fish except by laboratory analysis or by feeding the suspected fish to animals and watching for a reaction. The occurrence of fish containing ciguatoxin is unpredictable and can occur in a fish species that was harmless the day before. About 800 species of fish have been known to produce ciguatera, and common types that have been known to carry ciguatera include barracuda, grouper, snappers, jack, wrasse (Labridae), parrotfish (Scaridae), and surgeonfish (Acanthuridae). Toxic fish seem more prevalent in tropical areas and, because the concentration builds up over time, large fish of a given species are more likely to be toxic than smaller ones. The internal organs and roe of diseased fish are particularly toxic. Severe ciguatera poisoning may end in death, which is caused by respiratory paralysis. The toxin is not destroyed by cooking.

Symptoms and Signs

- Numbness of lips, tongue, throat
- Abdominal cramps
- Nausea, vomiting
- Diarrhea
- Weakness, prostration
- Reversal of thermal sensitivity (hot feels cold and cold feels hot)
- Muscle and joint aching
- Nervousness
- Metallic taste in mouth
- Visual disturbances
- Extreme fatigue
- Muscle paralysis
- Convulsions.

Treatment

There is no definitive first aid available for ciguatera poisoning. If symptoms occur within 4 hours of eating fish, vomiting should be induced. Medical attention should be sought as soon as possible, and the treatment team should be told that fish has been consumed within the last 30 hours. In some cases death occurs within 10 minutes, but a period of days is more common. If untreated, death may be caused by paralysis of the respiratory system. Careful observation for respiratory failure should be continued until medical help is reached, and CPR should be started if required.

18.14.2 Scrombroid Poisoning

Some scrombroid fish (tuna, bonito, mackeral, skipjack, etc.) that have been exposed to sunlight or been left standing at room temperature for several hours may develop a toxin and have a peppery or sharp taste. Within a few minutes of consumption, symptoms of this type of poisoning, which resemble a severe allergy, will develop. The symptoms usually clear within 8-12 hours.

Symptoms and Signs

- Nausea, vomiting
- Diarrhea
- Abdominal pain
- Severe headache
- Dizziness
- Massive red welts
- Severe itching
- Severe dehydration
- Shock.

Treatment

The victim should seek medical aid as soon as possible. Vomiting should be induced if it does not occur spontaneously.

18.14.3 Paralytic Shellfish Poisoning

During the summer months, many shellfish that inhabit the Pacific coast and Gulf of Mexico may become poisonous. This poison is caused by the ingestion of poisonous plankton and algae, which contain different types of toxins that do not affect the shellfish but can be poisonous to humans. Mussels and clams carry this poison, but abalone and crabs, which do not feed on plankton, are not affected. In most cases, cooking will not neutralize the toxin. The poison works directly on the central nervous system and the usual signs, such as nausea and vomiting, are not generally present. The poison impairs respiration and affects the circulation of the blood. Death, which occurs in severe cases, results from respiratory paralysis. Onset is variable but may occur within 20 minutes of ingestion.

Symptoms and Signs

- Tingling or burning of lips, mouth, tongue, or face, which spreads to other parts of the body
- Numbness
- Muscle weakness and paralysis
- Respiratory failure
- Infrequently, nausea, vomiting, and other gastrointestinal ailments.

Treatment

Vomiting should be induced as quickly as possible, and immediate medical attention should be sought. Rescuers should be prepared to provide mouth-to-mouth resuscitation or CPR.

SECTION 19
ACCIDENT MANAGEMENT AND EMERGENCY PROCEDURES

ACCIDENT MANAGEMENT AND EMERGENCY PROCEDURES

19

19.0 GENERAL

Accident management has a broader meaning than the term implies; it includes many activities, ranging from accident prevention to selection of personnel, equipment, and procedures and the emergency care of victims after an accident. Preventing accidents through proper training, forward planning, and the on-scene management of casualties is emphasized in this section, which applies only to open-water accidents. The reader should consult Sections 18 and 20 of this manual for first aid and treatment procedures.

Statistics on fatal scuba accidents show that accidents occur in clusters, particularly in areas where diving activity is concentrated, such as California, Florida, the Great Lakes, and off the Northwest coast. Although the number of dives undertaken per year has risen markedly, it seems likely that the actual incidence of accidents (i.e., number of accidents per unit time, or rate of accidents) has decreased on an annual basis. Reports of scuba fatalities indicate that proper accident management procedures frequently could have prevented the accident or saved a life once an accident occurred (McAniff 1986). Divers killed accidentally are usually found with intact equipment, weight belts on, functioning regulators, tanks containing some air, and uninflated buoyancy control devices. Instances in which equipment failure led to the death of the diver are extremely rare. Human error and inadequate diver performance seem to be the major contributing factors in many fatal accidents, and panic is probably the initiating cause in most instances. In some cases, a feeling of apprehension may precede panic and itself produce problems leading to a diving accident. Many divers are apprehensive, and even the experienced ones may be disturbed by certain kinds of water conditions or other circumstances associated with a particular dive. The competent diver is one who gains as much information as possible about the dive site, boat, equipment, and other important features of the dive. Planning prepares the diver to meet unexpected eventualities; a thorough knowledge of the dive site, including currents, marine hazards, and sea states, is essential to proper planning (see Section 10).

Panic

Panic is different from apprehension. One kind of panic involves the belief that an individual is losing control of his or her own performance and the situation. Panic is accompanied by severe physiological changes that may in turn facilitate loss of control. For example, an individual breathing rapidly and shallowly because of panic causes a buildup of carbon dioxide as a result of inadequate ventilatory exchange (see Section 3.1.3.9). Lowered air intake also can result in a loss of buoyancy and lead to inefficient swimming movements, which further contribute to a loss of control.

Stereotypical behavior also can result from panic. For example, a diver discovering that the air valve reserve mechanism has been tripped accidentally, leaving no reserve air, could respond properly either by releasing the weight belt and slowly ascending to the surface or by asking a buddy for assistance. On the other hand, the stereotypical response would be to continue pulling the reserve mechanism lever, causing greater panic and loss of control. The basic problem in many cases is that the diver delays releasing the weight belt or asking for assistance until the onset of panic, by which time he or she has probably lost the necessary degree of motor coordination to act effectively.

Before a diver reaches the point of panic, warning signs appear that should alert dive masters and dive partners to the presence of impending problems. Among the warning signs of panic in the water are indications of anxiety (primarily a change in breathing rate and pattern from smooth and regular to rapid and shallow) and changes in swimming movements (generally a shift from smooth and regular movements to jerky and irregular motions). A detailed discussion of the problem of panic appears in Bachrach and Egstrom (1986). The panicking diver frequently goes through desperate motions, such as "clawing" the surface, trying to hold the head above the water, and spitting out the mouthpiece, which only create further problems.

The best means of preventing panic is to make sure that a diver is well trained, especially in emergency procedures such as ditching the weight belt and operating the buoyancy compensator, well equipped, in good physical condition, and well informed about dive conditions and the purpose of the dive. The following paragraphs describe these aspects of dive planning.

19.1 ANTICIPATING A PROBLEM

Every diver should develop skill in recognizing the warning signs, either in himself, another diver, or the dive situation, that foreshadow a diving accident. This ability can significantly increase the chance of averting a fatality and thus can enhance the safety of both victim and rescuer. Danger signs exhibited by divers are both varied and subtle and may be apparent before or during the dive. A diver's ego may cause him or her to mask incompetence, anxiety, illness, or other distress before the dive, and features of the environment, such as difficulty in communication, may make it nearly impossible to observe such signs once the dive has begun.

19.1.1 During Training

The management of scuba accidents should begin when a candidate expresses an interest in learning to dive. The process of screening applicants before admitting students to a scuba training program should include obtaining medical releases from physicians and evaluating swimming and watermanship. (Most sport certification agencies require a physician's release only if something unusual is reported on the medical form.) During the in-water evaluation, the candidate should be required to demonstrate endurance and confidence in the water so that the instructor can assess whether the candidate is comfortable in the aquatic environment. Students should be encouraged to obtain breath-hold diving experience before beginning scuba lessons to enhance their ability and confidence in the use of mask, snorkel, fins, and other equipment and to maintain these skills throughout their diving career. Points for the instructor to observe include such things as breathing through the snorkel with the face (without a mask) in the water, surface diving to pick up an object in about 20 feet (6 meters) of water, and clearing the snorkel easily. Another good test of aquatic ability is having an unequipped swimmer catch his or her breath and rest while unsupported in deep water after a strenuous swim.

Throughout the preliminary training and evaluation, the instructor should estimate how the diver-candidate is likely to handle an emergency or react under stress and should identify the areas in which the student needs special attention and extra training. An area of training often neglected is learning the proper procedures for dressing and attachment of gear such as weight belts, buoyancy compensators, gauges, etc. These procedures should be overlearned to the extent that they become second nature, which ensures that equipment will be properly positioned in the event of an emergency.

Because panic is frequently involved in diving accidents, it is important that the student learn to feel confident and at ease in the water at the outset of training. Signs that indicate anxiety or a lack of confidence in the water are:

- Evidence of claustrophobia
- Expressed fear of and difficulty with underwater swimming
- Difficulty in adapting to mouth breathing
- Difficulty in adapting to underwater breathing using scuba apparatus
- Poor watermanship without swim or flotation aids
- Complaints about the regulator's breathing resistance
- Constant fidgeting with dive equipment
- Obvious overweighting
- Constant interest in swimming to the surface
- Rapid and/or shallow breathing
- Stiff and uncoordinated movements
- Reluctance to exhale fully when requested to do so by the instructor
- Hanging onto the instructor's hand too tightly when being escorted
- Becoming anxious when minor equipment problems occur on the bottom
- Lack of acknowledgment when the instructor looks directly into the eyes
- Constantly being "wide-eyed"
- Complaints of inability to clear the ears, especially during early open-water training.

Many other signs that reveal anxiety, fear, or incompetence can be observed. Although in most instances these problems can be overcome by proper training, some individuals, even with excellent training, are better advised not to pursue scuba diving.

Experienced divers sometimes can anticipate another diver's problems during open-water training. In such cases the experienced diver should observe the extent of the other diver's familiarity with equipment, ease in donning it, and ability to correct a leaky mask or put a regulator in the mouth under water. The experienced diver also should note whether the inexperienced diver swims off alone, oblivious to the buddy, and whether there is difficulty in breathing from the regulator with the mask off. Each of these occurrences may be a clue indicating that the student in question may subsequently panic easily or become overconfident. Even the best divers are concerned about becoming overconfident and seek advanced training when necessary.

19.1.2 During Dive Preparation

Although individuals suffering from serious illnesses or injuries usually make no attempt to dive, many divers enter the water with minor discomforts that may have adverse consequences, particularly if an emergency develops. Examples of such minor maladies are ear or sinus infections, headaches, lung congestion, seasickness, cramps, and the side effects of medication. Divers should assess not only their own condition but also that of other divers in the group.

Before entering the water, each diver should note the configuration, condition, and completeness of the buddy diver's equipment. The overequipped diver encumbered with more equipment than can be handled safely in the water should be advised to leave nonessential items on the shore or in the boat. During predive preparations, every diver should be alert to signs of diver ineptness or error, such as lack of knowledge of procedures, nervousness, or mistakes made while assembling equipment.

Other signs of potential problems are more subtle and psychological in nature; included in this category are changes in personal characteristics, such as an increase in the pitch of the voice, incessant chattering, procrastinating before actually entering the water, and withdrawal. Signs of overheating or chilling, such as excessive sweating or shivering, also should be noted. These signs should be responded to before entering the water, either by providing direct assistance (if the problem is mechanical), by giving reassurance, by practicing a particular skill, or by suggesting that the individual not dive (if circumstances warrant). Although some divers might be embarrassed by the latter suggestion, others might welcome it with relief.

19.1.3 During Entry and Descent

Failure to use proper entry techniques or forgetting essential equipment such as fins or mask may be signs that the diver requires watching. Other hints that the diver may be under stress or uncomfortable in the water are failure to surface properly or to check with the buddy before descent and excessive "high treading." High treading means that the diver treads and fins with vigor sufficient to lift the major portion of the body out of the water without using buoyancy compensation. When this activity is accompanied by dog paddling and using the arms excessively, it is a sign that a potentially serious problem may be in the making. Rejecting the mask or other essential equipment in the water is also a portent of problems, as is the tendency to cling to or clamber onto objects above the surface (not to be confused with the normal practice of using a float or some other object for temporary support).

Once the descent begins, there may be other signs that a problem is developing. Although anyone can have occasional difficulty with ear clearing or buoyancy control, chronic problems or overconcern may indicate an uneasy diver who needs watching. Ear equalization problems at depths below 50 feet (15.2 meters) are particularly indicative of a potential problem. Sudden changes in descent rate also should be noted because they may indicate either overconfidence or a desire to return to the surface. Throughout the descent and initial phase of the dive, every diver should observe his or her buddy for signs of erratic behavior, such as abrupt changes in swimming speed, fiddling with equipment, lack of stability, or difficulty with buoyancy control. Sudden or unnecessary use of the hands and arms for propulsion or buoyancy often is a sign of anxiety and impending difficulty. The diver exhibiting any or all of these signs may be unaware that anything is out of the ordinary, but experienced divers should be sensitive to such behavior before a problem develops.

19.1.4 During the Dive

Once entry and descent have been achieved, the alert diver continues to watch for signs that suggest an approaching problem. The things to watch for are basically the same as those during descent, i.e., general uneasiness, fast breathing, straying from the buddy, erratic behavior, or equipment problems. Any deviation from good diving practice, such as failure to check the air supply, depth, and time, should be mentally noted. Diving accidents are particularly likely to happen either in the first 3 minutes of a dive (because of lack of preparedness) or in the final 5 minutes (because the dive has been extended too long). Photographer-divers should be watched especially carefully because it is easy to become preoccupied with the task at hand and to forget to keep track of time, depth, and air supply. It is also important to keep track of significant changes in surface conditions or currents that might affect ascent or exit from the water. In conditions of poor visibility or during night dives, extra care must be taken to ensure that lights are functioning properly and that divers stay close together. In addition, at least one diver should watch for potentially dangerous marine animals if they are known to exist in the area.

At the end of the dive, divers should surface in buddy pairs. Prior arrangements about when and where the dive will be terminated should have been made before beginning the dive.

19.1.5 During Ascent and Exit

It is especially important to maintain a continual awareness of potential problems at the end of a dive.

Several factors can contribute to carelessness and accidents, such as fatigue, cold, equipment malfunction, and overconfidence. In observing a buddy diver during ascent, it is essential to note whether the no-decompression time has been exceeded, the rate of ascent is too rapid (especially during the last 10 feet (3 meters)), the distance between divers is too great, or that surfacing will take place either where there are obstacles (kelp, active boat channels, rip current, breaking waves) or down current from the support platform. Proper attention also must be given to ensuring an adequate air supply and that the buddy is breathing properly during ascent.

Each diver should ensure that the buddy does not exit from the wrong place in the surf line, exit to an unsafe surface in a heavy surge, get too close to a dive platform in a heavy swell, or hang on tightly to a line attached to the bottom during a heavy swell. Because divers are often fatigued at the end of a dive, extra caution must be paid to the routine handling of equipment while climbing up a ladder or into a boat. In particular, divers should avoid coming up the ladder under the tank or the falling zone of another diver.

WARNING

Unless the Diver is Exhaling When the Trough of the Wave Passes Overhead, Hanging onto a Line Attached to the Bottom in Heavy Swells is Dangerous Because the Change in Pressure May Cause an Embolism

19.2 CAUSES OF EMERGENCIES

Diving emergencies can arise from an almost infinite number of causes, including exhaustion, embolism, decompression sickness, nitrogen narcosis, heart attacks, high currents, entanglement, heavy surf, out-of-air emergencies, equipment failure, and panic. In general, diving accidents are overwhelmingly caused by human error rather than equipment failure. The probable causes of non-occupational diving fatalities are summarized in Table 19-1, which shows that only 12 percent of fatalities occurring over a 9-year period were attributable directly to equipment malfunction. Readers interested in more details about the causes of diving fatalities should consult McAniff (1986).

In the planning stages of a dive, contingency plans should be made, and all divers should be briefed and familiarized with those plans. New or unfamiliar equipment should be understood thoroughly by all divers, and practice sessions should be held before the dive.

Before initiating a dive, experienced dive masters visualize the worst accident scenarios and mentally rehearse the management of these hypothetical accidents. It is even more effective to sketch an accident management flow diagram (Somers 1986). In planning, it is essential to assess the capabilities of the dive team to ensure that, in the event of an accident, novice divers are not unnecessarily exposed to risks.

No matter how well planned the dive or how well trained the diver, however, emergency situations occasionally arise, usually as a result of failure to observe some safety precaution. In most instances, taking a few seconds to assess the situation accurately and determine the actions necessary can keep the emergency from becoming an accident. Instinctive reactions seldom are correct and may prove to be blind impulses brought on by panic. Adequate training should prepare the diver for most emergencies, provided that panic does not intervene.

The following paragraphs describe some of the more common causes of diving emergencies and methods of avoiding and managing emergencies if they do occur.

19.2.1 Loss of Air Supply

The first step in evaluating an out-of-air situation should be to confirm that the apparent air loss is real. Before reacting precipitously, the diver should stop, think, attempt to breathe, and, if it is possible to do so, proceed with a normal ascent. Students should be taught that many out-of-air situations are related to the diver or the situation rather than to the equipment or actual loss of air supply. If considered before resorting to emergency procedures, the human aspects of apparent air loss situations often can be corrected (Kent 1979).

If a diver determines that his or her air supply is depleted, experts recommend that the diver initiate an independent action such as a controlled emergency ascent or use of an alternative personal breathing apparatus (when feasible) (Egstrom 1984). If it is not possible to institute an independent response, a dependent action (e.g., buddy breathing, alternate stage breathing, breathing from an inflated buoyancy compensator (BC), use of an auxiliary scuba cylinder) should be considered. As a last resort, an emergency buoyant ascent may be necessary.

It has been found that *breathing from an inflated or partially inflated BC* is a safe practice in an emergency situation if proper procedures are followed (Pierce 1983, Bove 1985). If this technique is used, it is essential that the bag be flexible and be prevented from becoming overinflated as the diver ascends. If the bag loses its flexibility as a result of overinflation, it can

Table 19-1
Summary of Probable Causes of Non-Occupational Diving Fatalities from 1976-1984

Probable Cause of Accident	1976	1977	1978	1979	1980	1981	1982	1983	1984	Total
Medical condition or injury	49 (33)	51 (50)	45 (39)	62 (44)	54 (49)	27 (26)	33 (44)	47 (43)	25 (36)	393 (41)
Environmental condition	45 (31)	19 (19)	26 (22)	29 (21)	28 (26)	43 (42)	16 (22)	33 (30)	16 (23)	255 (26)
Equipment	14 (10)	19 (19)	22 (19)	19 (14)	14 (13)	9 (9)	8 (11)	6 (5)	3 (4)	114 (12)
Unknown	39 (26)	13 (12)	23 (20)	29 (21)	13 (12)	24 (23)	17 (23)	24 (22)	26 (37)	208 (21)
Total	147	102	116	139	109	103	74	110	70	970

Values in parentheses are percentage of all scuba fatalities reported for the year.

Derived from McAniff (1986)

cause a lung overpressure accident by forcing too much air into the lungs on inhalation or by causing an excessive rate of ascent. Inhaling water while using the BC mouthpiece can be avoided by proper purging. Divers can rebreathe exhaled air safely for as long as one full minute without incurring any adverse physiological effects (Bove 1985).

Many divers choose to equip their scuba cylinders with two *second-stage hoses with regulators (octopus)* to use for emergency buddy breathing or in case the primary regulator fails. The use of an octopus is considered one of the more desirable options in out-of-air situations and is recommended by the major sport diving training agencies (Graver 1985). If this technique is used, the octopus hose should be at least 12 inches (30.5 centimeters) longer than the primary hose, be marked for easy identification, and be oriented so that it will always be right side up when used. When using an octopus system, the distressed diver should notify the buddy that air is needed and should then proceed to breathe from the extra regulator. Since the air supply of the buddy also is likely to be low, ascent should begin immediately after a brief stabilization period. Two persons breathing from a tank with a low air volume through a single first stage can quickly deplete the air supply. Also, in cold water, the extra flow may cause the regulator to freeze. The divers should maintain physical contact by holding onto each other's straps.

Auxiliary scuba cylinders attached to the primary cylinder can be used as an emergency air source, and their use is recommended in some cases (Graver 1987). Such cylinders can be obtained in sizes ranging from 1.7 to 15 cubic feet (0.05 to 0.4 cubic meter) and normally are used with a separate regulator. They are designed as an emergency system only. For example, a 4 cubic foot (0.11 cubic meter) cylinder provides about 14 to 16 breaths at a depth of 100 feet (30.5 meters) and about 80 breaths in shallow water (Anonymous 1984).

If loss of air is sudden and unexpected and no auxiliary air sources are available, *buddy breathing utilizing a single regulator* may be necessary. Often, the distressed diver will begin to cough or choke. Until the diver's condition has stabilized, both the diver and buddy should maintain their depth while continuing to buddy breathe. Air donors should allow the victim to use their air supply as much as is possible without jeopardizing their own supply. When the distressed diver's condition has stabilized, a safer ascent can be made.

If it is necessary to remove the distressed diver's equipment, the ascent should be stopped while the equipment is removed. Because equipment removal will distract the diver and interrupt the breathing pattern, increasing the possibility of gas embolism, this step should only be undertaken when absolutely essential. Every effort should be made to maintain an ascent rate no greater than 60 feet (18.3 meters) per minute.

The most efficient method of buddy breathing is for the two divers to face each other, each alternately breathing from the same mouthpiece while ascending (Figure 19-1). During the exchange of the mouthpiece, the exhaust valve on single-hose regulators must be positioned below the mouthpiece so that water can be eliminated from the second stage; this position can be achieved conveniently if the divers are side by side, with the diver in distress on the left. The donor controls the air, and both divers must exhale between exchanges. Contact should be maintained by having each diver hold the straps or belt of the other diver.

Figure 19-1
Buddy Breathing

Source: NOAA (1979)

WARNING

During Buddy Breathing, One Diver Should Be Breathing From the Regulator While the Other Diver Is Exhaling

When using constant-volume dry suits or large buoyancy compensators, extra precautions should be taken to prevent uncontrolled ascent caused by air expansion of the suit as the diver rises in the water column. For example, the normal procedure of dropping the weight belt should not be followed when a constant-volume dry suit is used unless the suit is flooded. During ascent, the amount of air in the dry suit or partially inflated buoyancy compensator should be controlled by the exhaust valves or use of another venting method such as opening a cuff.

If it is necessary to cover a horizontal distance while buddy breathing, a number of different methods can be used. The two most common are for the divers to swim side by side (about halfway on their sides), facing each other, or to swim one above the other, the diver with the good air supply on the bottom. In this manner, the mouthpiece can easily be passed back and forth between divers.

WARNING

When One Diver Runs Out of Air, the Buddy's Supply Is Also Usually Very Low. With Double Consumption, the Available Air Can Be Depleted in Seconds. Buddy Breathing Ascent Should Therefore Be Prompt

If buddy breathing is not possible, the diver can make an *emergency buoyant ascent* to the surface while venting air continuously. Unless the breathing apparatus is entangled, however, a diver should not abandon it. The reduction of ambient pressure as the diver rises to the surface increases the pressure differential, providing additional air for breathing from the scuba and allowing the diver to make a controlled ascent. Trying to breathe by sucking on the regulator or swallowing may decrease the urge to breathe during ascent, but divers should remember not to hold their breaths while employing these tactics.

WARNING

Emergency Buoyant Ascents Are Difficult and Hazardous and Should Be Used Only as a Last Resort to Resolve an Emergency Situation

When using constant-volume dry suits or large buoyancy compensators, extra caution should be taken to prevent uncontrolled ascent. Spreading the arms and legs increases drag and stability and slows the rate of ascent. The diver must continue to exhale throughout the ascent. The head should be extended back, allowing maximal opening of the throat and a good overhead view. The diver should swim to the surface, staying constantly aware of possible entanglements or obstructions and the consequences of breath-holding. The mouthpiece should be left in place.

WARNING

If the Diver Is Having Difficulty Ascending, the Weight Belt Should Be Released Immediately. Make Sure No Divers Are Below Before Dropping the Belt

At night or when visibility is low, the diver should exert extra care to hold his or her hand over the head during ascent to prevent it from hitting a boat or some other object on the way up.

WARNING

Discarding Self-Contained Equipment and Making a Free Ascent Should Be Considered Only as a Last Resort. When This Procedure Must Be Used, Exhale All the Way to the Surface (see Section 3.2.2)

Regardless of the out-of-air emergency response system used, certain criteria should be met. Egstrom (1984) has listed the essential ones:

- the procedure should be standardized;
- it should be simple;
- it should require only a minimal amount of skill to implement;
- it should be reliable and effective;
- it should involve a minimum amount of retraining;
- it should not be expensive.

All of these emergency techniques require learning of skills and must be practiced to the point of overlearning. For example, a study conducted by the staff of the University of California, Los Angeles, Diving Safety Research Project found that students who had practiced buddy breathing on 17-21 successful trials were able to perform without errors (Egstrom 1984). Practice while swimming was more effective than practicing while sitting on the bottom of the pool. When diving with a familiar partner and equipment, buddy breathing should be practiced periodically. This is even more important when either the partner or the equipment is unfamiliar. (For additional information on ascents, see Section 19.5.2.)

19.2.2 Loss or Flooding of Equipment

Flooding of a face mask may be caused by another diver inadvertently kicking the mask loose with a fin, by high currents, or by turning the head into a rock, net, or other obstruction. The mask can be cleared by tilting the head back, pressing the top of the mask against the forehead, and blowing into the mask through the nose (Figure 19-2). The air will displace the water, forcing it out the bottom of the mask. When the mask is equipped with a purge valve, the diver should position his or her head so that the purge valve is in the lowest position relative to the mask, hold the mask against the face, and then exhale through his or her nose. If the mask is lost, divers should fix their position, wave one hand over their heads, and have their partner come to them.

When the second stage of the regulator is lost, the hose generally remains lying over the diver's right shoulder. If it is not, it can be located by reaching back over the right shoulder with the right hand, grasping the first stage of the regulator at the tank's valve to locate the hose where it joins the first stage, and then following the hose out to the mouthpiece. The mouthpiece probably will be flooded, but it can be cleared by a sharp exhalation or by pushing the purge button.

With a double-hose regulator, the mouthpiece and hose will float above the diver's head. One method of recovery is for the diver to roll onto his or her back. The hose and mouthpiece will then float above the diver's face. When the mouthpiece of a double-hose regulator is above the level of the regulator, it will free flow. The hose and mouthpiece can be cleared of water by holding the mouthpiece above the head. If the exhaust hose is flooded, it can be cleared after the mouthpiece is back in the mouth by exhaling or rolling over on the left side, which allows the water to flow the length of the exhaust hose and be forced out the air exhaust valve. If a double-hose regulator is to be used, the diver should practice clearing it.

19.2.3 Fouling and Entanglement

When a diver becomes trapped, entangled, or fouled, it is important to make a calm assessment of the situation. Struggling generally results in even deeper entanglement and damage to, or loss of, diving equipment. Scuba divers should be more concerned about entanglement than other types of divers, because their air supply is limited and communication with the surface usually is not possible. Maintaining a cool head, using common sense, the presence of a nearby buddy diver, and use of a diving knife usually suffice to gain freedom from entanglement. Emergency free ascent should be used only as a last resort. When the dive is in the surface-supplied mode, the diver should notify surface personnel as soon as the entanglement occurs. If the diver cannot become untangled promptly, the assistance of a standby diver should be requested.

Figure 19-2
Clearing a Face Mask

Source: NOAA Office of Undersea Research

19.2.4 Near Drowning

The most common antecedent to drowning is panic, which occurs when divers find themselves in a position for which they are mentally or physically unprepared. The majority of drownings can be avoided if the diver is trained properly, is in good physical condition, and is using reliable, well-maintained equipment.

The most important step in the immediate treatment of a near-drowning victim is to restore breathing (see Section 18.1.5). The most effective means of artificial resuscitation (when used by trained personnel) is a mechanical resuscitator. If one is not available, artificial resuscitation is required; the most effective form is mouth-to-mouth resuscitation. This method is simple and can be administered to a victim still in the water (see Section 19.5.1). Victims of near drowning in water at a temperature of less than 70°F (21°C) may appear to be dead and yet have a significant chance of survival if cardiopulmonary resuscitation is started immediately. Recovery has occurred even after submersion in cold water for periods of up to 40 minutes (see Section 18.1.5). The chances of recovering increase if the victim is young and the water is cold.

19.3 ASSESSING A PROBLEM

Obvious indicators of diver distress that most swimmers and rescuers recognize easily include cries for help, arm or whistle signals (see Section 14.2), an actively struggling diver, or one who appears ill or unconscious. Because scuba divers should always dive in pairs, finding one drowned or distressed diver may mean that the buddy has also succumbed or is in distress. In some cases, there is no forewarning of serious trouble. For example, an exhausted diver may simply slip quietly and suddenly beneath the surface without a sound. Indications of anxiety or difficulty may be suppressed either because of ego (unwillingness to admit having a problem) or may actually be hidden by the face mask or other diving equipment. As discussed earlier, high treading, clinging, clambering, and removing equipment are all signs of impending trouble.

Regardless of how the rescuer becomes aware that a diver is in distress or whether the emergency occurs on the surface or under water, the first step is a rapid but thorough assessment of the situation. Factors that should be considered at the outset are location and distance to the victim, ability to establish and maintain visual contact, and the availability of additional assistance (personnel and equipment). It is not advisable even for a trained rescuer to attempt to rescue a diver without taking the appropriate equipment. For example, rescue in the surf should not be made without fins. Dive boats usually have readily accessible life-saving floats, seat cushions, and ring-buoys that can be thrown. There may also be surf boards, floats, buoys, and rescue boards on the beach. Rescuers should assess their own ability to carry out a rescue. The rescue hierarchy is reach-throw-row-go, i.e., the first choice of strategy should be to reach the victim by boat or other means, followed by throwing a lifeline or ring buoy, and so on to the last step, which involves a rescuer going to the aid of the victim in the water. If more than one person is in a group, the individual or individuals most suited to perform a rescue should be selected immediately, while others are assigned to stay with the boat, use the radio, obtain flotation equipment, and perform other necessary tasks, which are particularly important if there are adverse environmental conditions, such as poor visibility, high currents, or poor surface conditions. If the victim is under water, overhead obstructions may further complicate the situation.

As the victim is approached, the rescuer should try to determine the nature of the problem—whether the problem is caused by entanglement, a strong current, a rough sea, or some other environmental factor. Other possible causes of distress include nausea, decompression sickness, embolism, contact with a poisonous marine animal, or equipment problems. Being familiar with the victim's equipment is an important part of the overall assessment. If the weight belt is to be released, care must be taken to ensure that it falls clear of both the victim and the rescuer and that the waist strap of the backpack is not confused with the weight belt.

WARNING

Divers Experiencing Stress at the Surface Should Drop the Weight Belt Immediately to Ensure That They Will Float Sufficiently High in the Water

The rescuer should note immediately the location of the CO_2 inflator for the buoyancy compensator and activate the appropriate mechanism or begin oral inflation. Many BC's available on the market do not have CO_2 inflators, although these can be purchased separately and installed. If it is necessary to ditch the backpack, most systems require the release of both the waist belt and at least one shoulder strap.

Of primary importance is the state of the victim. If unconscious and under water, the victim must be brought to the surface quickly. If unconscious and on the surface, the method of handling will differ from that of a conscious victim. If the victim is conscious, the rescuer must assess the victim's mental state and then proceed in a manner that does not increase the victim's pain, induce panic, or complicate existing injuries or the rescue process. Finally, the rescuer must assess the victim's state of buoyancy. If the victim is not positive, the rescuer should take immediate action to establish positive buoyancy. An additional factor that must be assessed is the method of transporting the victim to shore. For example, returning the victim to the starting point of the dive may not be the best procedure because other locations may be more accessible, have essential lifesaving equipment, or be more suitable for administering first aid.

19.4 APPROACHING A VICTIM

The approach is defined as those events taking place between the time the rescuer initiates action and physical contact is established with the victim. One of the first decisions to be made is whether or not a swimming rescue is necessary. An extension rescue, one involving lines, poles, ring buoys, or rescue throw bags, is usually safer and more desirable. Rescue throw bags, which provide a 60 to 70 foot (18.3 to 21.3 meter) 'extension' of the rescuer's arm, are now accepted pieces of rescue equipment. If two rescuers are involved, one can attempt an extension rescue while the other initiates a swimming rescue. Situations requiring a swimming rescue include those involving a submerged victim, a victim unable to respond adequately to verbal instructions, or a victim losing the battle to stay afloat.

NOTE

Water safety authorities strongly advocate that the rescuer avoid coming into physical contact with an unstabilized victim, if possible.

In all cases of a swimming rescue, the rescuer should continue trying to enlist help as long as possible. The victim should be observed continuously at all times because the victim may sink, become unconscious, become panicky, or stop breathing. When a rescuer is approaching a submerged victim, especially in water with poor visibility, two observers stationed at fixed points (boat or shore) pointing at the place of the victim's submergence provide a bearing for the rescuer.

If the victim is conscious and on the surface, the rescuer should explain what is going to happen and make every effort to calm the victim. If the victim is submerged and conscious, conventional hand signals should be used and the rescuer should demonstrate exactly what the victim is expected to do. Positive buoyancy should be established for the victim immediately. If the victim's equipment is to be ditched, it is recommended that it be handed to the rescuer rather than dropped, because this makes it more likely that it will fall clear of the body. Depending on the situation, rescuers also may have to remove their own equipment, such as the tank or weight belt, to facilitate the rescue. Upon reaching the victim, the rescuer should pause momentarily to reasses the situation and to rest briefly before establishing physical contact.

19.5 RESCUE PROCEDURES

Although certain rescue procedures should be considered standard, the trained rescuer must still use common sense because no two emergencies are identical. The following procedures are not intended to be an exhaustive treatment of scuba lifesaving techniques but rather to alert the reader to these rescue procedures. (For further information, the reader is referred to Seiff 1985, Pierce 1985, Somers 1986, Anonymous 1986.)

When attempting any of the rescue procedures described in the following paragraphs, the diver should be careful not to become entrapped by the victim or the result may be a double casualty. The first concern of rescuers when they are seized by a struggling victim must be for their own safety. One way to escape from a victim's grasp is to inflate the victim's or the rescuer's buoyancy system, which will push the divers apart.

19.5.1 Victim Submerged and Unconscious

An unconscious, unbreathing victim, whether submerged or at the surface, is in imminent danger of death. Virtually all of the rescuer's efforts must be directed at initiating and maintaining artificial resuscitation. Since resuscitation cannot be administered under water, the first consideration of the rescuer should be to get the victim to the surface.

WARNING

No Resuscitative Efforts Should Be Attempted While Submerged

The rescuer should establish positive buoyancy as soon as possible and bring the victim to the surface in a controlled buoyant ascent. The rescuer should approach the victim and remove the weight belt. If this is not possible, the BC should be inflated to achieve a slight positive buoyancy. Rescuers may need to remove their own weight belts and adjust their BC's to ensure that they are not more buoyant than the victim. As described in Seiff (1985), the victim should then be placed in a left-sided do-si-do position with the head tilted back and be brought to the surface at a normal rate of ascent. In this position, expanding gases in the victim's lungs should escape without difficulty. The do-si-do is a swimming carry that affords the rescuer maximum mobility while controlling the victim (see Figure 19-3). The left upper arms are interlocked so that the rescuer can increase his or her control over the victim by squeezing the victim's arm between the rescuer's arm and chest. The rescuer always should be on the left side of the victim to facilitate control of the power inflator hoses on both the victim's and rescuer's BC's.

WARNING

Rescuers Should Be Careful Not to Risk Embolism or Decompression Sickness by Ascending Too Fast With An Unconscious Victim

Once the unconscious diver is on the surface (weight belt already removed, buoyancy compensator inflated, and mask off) and it has been determined that there is no breathing, the rescuer should be positioned for mouth-to-mouth artificial resuscitation. Based on in-water tests, it is recommended that the rescuer's mask be left on to retain optimal visual capabilities (Orr 1981). Removal of the victim's mask may be enough to start the victim breathing again. The best method for controlling the victim's position in the water while performing mouth-to-mouth resuscitation is the do-si-do position, shown in Figure 19-3.

The procedure for in-water mouth-to-mouth artificial resuscitation is:

- With the victim in a face-up position, slide your arm between the body and the same arm of the victim (see Figure 19-3). Remain on the victim's left side for ease of controlling BC power inflators.
- Reach back, grasp the victim's hair, hood, or buoyancy compensator, and pull back to place the victim in a level position and to drop his or her head to open the airway.
- Place the heel of your other hand on the victim's forehead and seal the nose with your thumb and forefinger (see Figure 19-4).
- Seal your mouth over the victim's mouth and give two slow, deep inflations to re-establish an adequate oxygen level. Do not pull yourself up over the victim to start resuscitation; this will tend to force the victim's head under water. Instead, simply roll the victim's head over to a position that allows you to seal the victim's mouth with yours

Figure 19-3
Do-Si-Do Position for Administering In-Water Mouth-to-Mouth Artificial Resuscitation

Source: NOAA Office of Undersea Research

with a minimum amount of kicking effort on your part.

- If there is resistance to lung inflation, pull the victim's head back further and try again. If this does not work, check the airway for blockage. If a foreign object or vomit is present, remove the obstruction quickly with your fingers before continuing attempts to inflate the victim's lungs.
- After successfully completing the two inflations, continue ventilating the victim's lungs at approximately 12 breaths per minute. The ventilation rate is not as important as filling the victim's lungs with each breath.

Sea conditions may override a controlled ventilation rate and require that the rate be modified to meet the sea's rhythm. This is accomplished by timing the ventilations to occur when the waves are washing over the victim's face. While continuing to resuscitate the victim, the rescuer should start swimming toward the beach or boat at a comfortable pace. The rescuer should be careful not to overexert during the rescue attempt. If it is necessary to use one arm for swimming, the rescuer can achieve a nose seal by pressing his or her cheek against the victim's nose. If two rescuers are present, one should be stationed at the head and one at the feet. The rescuer at the head is in charge. If three rescuers are available, two should be at the head and one at the feet (to push). The tank, BC, and weight belt (if still attached) should be removed from both victim and rescuers prior to bringing the victim on board a vessel or on shore.

Figure 19-4
Mouth-to-Mouth In-Water Artificial Resuscitation

Derived from photo by Dan Orr, Wright State University

NOTE

A single rescuer should angle the kick downward and toward the victim's feet, which not only provides some momentum toward shore or a boat but also tends to keep the faces of both rescuer and victim out of the water. Care must be taken not to overinflate the buoyancy compensators because the bulk created may prevent the rescuer from getting close enough to permit good mouth-to-mouth contact.

Mouth-to-mouth resuscitation requires no equipment and can be started immediately but is difficult to sustain for any period, especially in rough water. In addition, because the victim's mouth is open during exhalation, water may enter the victim's mouth.

A somewhat more energy-conserving method of performing artificial resuscitation in the water is mouth-to-snorkel artificial resuscitation (Figure 19-5). Using the snorkel to resuscitate the victim allows the rescuer to be positioned lower in the water, reducing the amount of kicking effort required to keep the head above water. To perform mouth-to-snorkel artificial resuscitation effectively, training is essential and continued practice is recommended. General procedures for administering mouth-to-snorkel artificial resuscitation are as follows:

- After the victim has been brought to the surface, administer two slow inflations, using mouth-to-mouth artificial resuscitation.
- Bend the snorkel and place it in the victim's mouth, keeping it between the middle and ring fingers as shown in Figure 19-5A. Make sure it is pressed down tightly around the flange. Seal the nose with the thumb and forefinger of the same hand, as shown in Figure 19-5B. It is not necessary to pinch the victim's nose, since the side of the rescuer's index finger will make the seal if pushed against the victim's nostrils. The best mouth seal can be made if the snorkel is inserted between the victim's lips and teeth. This may not be easy to do and time should not be wasted in the attempt because an adequate seal may be made by pressing the flange tightly over the outside of the lips.
- Place the victim in the standard chin-pull position with the head against the rescuer's chest, as shown in Figure 19-6.
- Place the tube end of the snorkel in your mouth and blow. It is necessary to blow longer than with

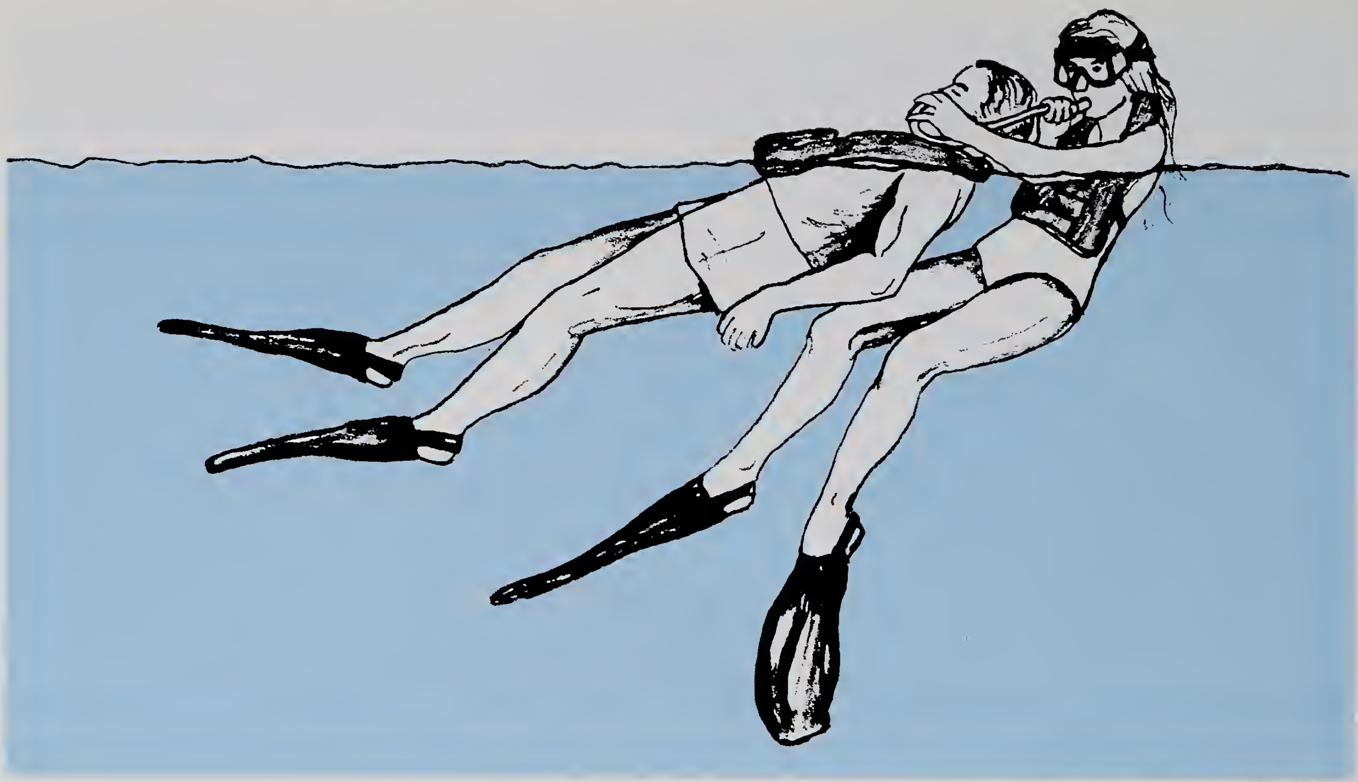
Figure 19-5
Mouth-to-Snorkel Artificial Resuscitation

A. Bending the snorkel and placing it in the victim's mouth

B. Getting a seal

Reprinted from *Scuba Life Saving,* pub. Royal Life Saving Society, Canada, 1987

Figure 19-6
Towing Position for
Mouth-to-Snorkel Artificial Resuscitation



Source: NOAA Office of Undersea Research

mouth-to-mouth resuscitation to overcome the dead air space in the snorkel.

- After filling the victim's lungs, remove the tube end from your mouth and allow the victim's air to escape through the tube. Although the chest cannot be seen to rise and fall, the rescuer can hear the air passing through the tube or feel it on the cheek.
- Continue to check to ensure that an adequate seal is maintained. A perfect seal is not essential, but an effort should be made to minimize escaping air.
- The victim should be checked continually to ensure that there is no choking or vomiting.
- Continue to ventilate the victim's lungs during the tow to the beach or boat. The victim's lungs should be filled with each breath to ensure that fresh air, rather than stale, is being provided. If the rescuer begins to feel dizzy because of hyperventilation, the rate can be slowed down.

Some snorkels work better than others because of shape, corrugations, or flexibility. Divers should check their snorkels and practice the procedures described above. Further details of in-water artificial resuscitation are described elsewhere (Smith and Allen 1978; Pierce 1977, 1985).

If the submerged victim is unconscious but still breathing, the rescuer should hold the victim's mouthpiece in place to ensure a good seal, achieve positive buoyancy, and proceed with a controlled buoyant ascent to the surface. The victim should be kept in a vertical position with the head in a normal, straight forward, but not hyperextended attitude.

19.5.2 Victim Submerged and Conscious

An assessment of the condition of a submerged victim may reveal any one of a variety of situations, each requiring a different form of contact and handling. When approaching a conscious submerged victim, eye contact should be established immediately and the victim should be signaled to stop swimming and hold onto a solid object, if one is available.

If both the victim and the rescuer are suspended in the water column, the rescuer should immediately neutralize the victim's buoyancy and drop the victim's weight belt or neutralize the buoyancy by appropriate means if the victim is wearing a dry suit or variable-volume wet suit. The rescuer should then neutralize his or her own buoyancy. When making physical contact with the victim, the rescuer should be alert for sudden grasping motions or rapid ascents; initially the rescuer should offer a hand only. If at all possible, only highly trained divers should attempt a mid-water rescue.

Stabilizing the victim may be enough to rectify the problem, assuming that the anxiety or distress was not caused by a problem such as entanglement or injury. Attempts to ascend with the victim before stabilization are not advised because the situation may continue to deteriorate uncontrollably. After stabilization, the rescuer should, in almost all cases, signal and initiate a controlled ascent while maintaining both eye and physical contact with the distressed diver. If, after reaching the surface, the victim still shows signs of anxiety or stress, the dive should be terminated. If the submerged victim is entangled, the first action of the rescuer is to provide a source of air (if needed), calm the victim, and tell the victim what will be done next. Knives or other tools should be used with great caution and the rescuer should remain alert for renewed struggling on the part of the victim during disentanglement. Except in cases of a minor snag, the victim and buddy should return to the surface and at least temporarily terminate the dive. Reassessment of both victim and equipment should be made on shore or support vessel.

An injured or ill diver should be taken to the surface at a reasonable rate of ascent, with care taken to maintain breathing. Depending on the severity of the injury or illness, the victim may have to be assisted by buoyancy control or propulsion during ascent. The ascent should be interrupted only if breathing is impaired by vomiting or other aspects of the injury or illness and should be continued as soon as breathing has been restored. Limited first aid or treatment of a particularly serious injury, e.g., hand pressure on a severe laceration, can be performed during ascent, but should not be allowed to interfere with the victim's breathing or with continuing ascent. In an injury involving serious bleeding, the rescuer should stay alert for predators in the water both during the ascent and after surfacing.

An *uncontrolled descent* caused by loss of buoyancy can create problems for the diver and rescuer even in relatively shallow waters, because of the danger of barotrauma or impact with bottom features. Uncontrolled descents in deep water may be complicated by nitrogen narcosis and can involve very serious problems of oxygen poisoning, rapid air consumption, and subsequent drowning. In this situation, a rescuer must quickly assess the risk and make a decision. In shallow water, for example, it may not seem prudent to risk ear squeeze to rescue a diver who is certain to come to rest on a shallow bottom and who will almost certainly be able to be rescued by a conservative rescue procedure. A diver descending uncontrollably in very deep water, however, presents a serious dilemma for the would-be rescuer. Variables to be quickly assessed include not only the victim's situation, but the potential rescuer's capabilities, air supply, susceptibility to narcosis, and so forth. Only a rescuer can make this personal decision. A wrong decision can mean the loss of two divers instead of one.

In such situations, the possibility of a rescue without physical contact should not be overlooked. An attempt should be made to get the descending diver's attention by banging on a tank or possibly even dropping an object past the descending diver's line of vision. Then, the diver can be motioned to the surface if the problem has simply been a lack of attention or concern. Visual contact serves at least to arrest the victim's descent long enough for a pursuing rescuer to reach that depth.

If pursuit of a descending diver is successful, the first contact should almost always be made from behind the victim. This permits grasping the tank valve of a diver dropping in a vertical feet-first position or in a horizontal plane. A diver dropping in a head-first position should first be grasped by the fin(s) to retard descent and to arrest any propulsive action. In such cases, the rescuer should quickly "climb" down the descending diver to grasp the tank valve. In situations where narcosis may be a factor for either party, the rescuer should remain behind the victim while arresting the descent and initiating ascent. Before establishing contact with the victim and inflating the victim's buoyancy device, the rescuer should establish his or her own buoyancy. This ensures the safety of the rescuer and permits the rescuer to use his or her own oral inflator to add additional buoyancy rather than attempting to use the victim's inflation device.

If a descending victim is struggling or appears otherwise to be irrational, a rescuer should remain above and behind the victim to ensure his or her own safety. Divers not directly involved in handling the victim of uncontrolled descent should be sensitive to both the decompression and air supply needs of the victim and rescuer. They can pre-position additional scuba equipment or obtain other resources that might be necessary.

An *uncontrolled ascent* may be caused by a loss of buoyancy control or panic. Although rescue of such a victim requires an extremely rapid response, rescuers must first ensure that their own ventilation will be adequate during the rescue. The rescuer also should be aware of the fact that a rapidly ascending individual may be making a calculated emergency swimming ascent. "Rescuing" such a diver may create more problems than it solves.

Where obvious breath-holding is a factor, the main rescue objective is to arrest the ascent quickly. The rescuer should grab the most accessible part of the victim, which, on a rapidly ascending individual, may be the fins. This will serve not only to maintain contact but also will arrest the propulsive motion. The rescuer should shift the grasp immediately to the victim's ankle or leg because the victim could easily swim right out of his or her fins.

Victims not overly buoyant may be stopped simply by physical contact with a slightly negatively buoyant rescuer. As soon as possible in a rescue procedure, the rescuer should establish a position above the ascending victim. The most effective position is face to face, maintained by keeping a grip on the victim's buoyancy compensator. Eye contact can be established and the rescuer's other hand should be used to vent the victim's buoyancy compensator. Panicky ascending victims often claw desperately, and a rescuer must be alert to the possibility of losing his or her own mask or regulator during contact with a desperate victim.

During attempts to arrest uncontrolled ascent in deep water, the rescuer also must recognize that an ascent that initially is non-buoyant may become buoyant near the surface because of expanding air in the buoyancy compensators of both the victim and the rescuer. Attempts to use signals, demonstrations, and if necessary squeezes, pushes, or other, more vigorous thoracic pressures directed at the diaphragm should be made to make the victim exhale during uncontrolled ascent. Applying steady pressure may be safer and more effective than using a jab or punch.

19.5.3 Victim on the Surface and Unconscious

When confronted with an unconscious victim on the surface, speed is of the utmost importance. A surface approach is recommended because it affords continuous eye contact with the victim. Although some degree of positive buoyancy on the part of the victim may be assumed, many buoyancy compensators currently in use do not ensure that the face of a helpless victim will be maintained out of the water.

When approaching the victim, the rescuer should have positive buoyancy and the BC should be inflated as needed. The victim should be pulled to the face-up position and the weights and scuba tank dropped. It may be necessary for the rescuer to drop his or her weights and tank, also. If the equipment is not dropped at the outset, the rescuer may forget to do so, thus making the rescue much more hazardous. While maintaining contact, the victim should be placed in a left-sided do-si-do position (see Figure 19-3). Mouth-to-mouth resuscitation should be started as soon as possible and continued at the rate of one breath every 5 seconds while the victim is being transported to the dive platform or shore.

NOTE

At the present time, the administration of in-water cardiopulmonary resuscitation is not recommended (Kizer 1984). Its effectiveness, even in swimming pool conditions, has not been demonstrated successfully and to attempt it in the open water will delay getting the victim to a place where it could be administered properly.

19.5.4 Victim on the Surface and Conscious

When approaching a conscious victim on the surface, every effort should be made to utilize an extension rescue technique and to obtain help, as described in Section 19.4. The rescuer also must carefully assess the victim's mental state. If the victim is rational and coherent and no alternative rescue technique is available, the approach should probably be made from the front and on the surface, because this approach allows continuous eye contact and reassures the victim because it allows him or her to observe the rescuer's actions.

NOTE

If possible, get the victim to initiate self-rescue by weight belt ditching or inflating the buoyancy compensator. Use guile if necessary, e.g., say "Hand me your weights."

If the victim is panicky or struggling, a different approach is required. One technique requires the rescuer to approach the victim from the front and while submerged. This is generally a safe method because the victim will be extremely reluctant to go under water. Another technique involves a surface approach from the rear of the victim. Some prefer this approach because an unexpected wave or rescuer buoyancy problem is unlikely to bring the rescuer within the grasp of the victim. An approach from the rear facilitates the rescuer's grabbing the victim's tank valve, permits the rescuer to reach and activate the buoyancy device, to release the weight belt, and to disconnect the low-pressure inflator hose going to the buoyancy compensator. The rescuer also is in good towing position and can release the tank from the backpack, if necessary. However, it is better not to surprise a victim and in most instances the rescuer will be seen or heard even when approaching from the rear. Thus, the rear approach frequently will become a frontal approach because the victim will turn to face the rescuer.

Once physical contact has been made between the victim and the rescuer, the first action of the rescuer should be establishing victim buoyancy by releasing the victim's weight belt and inflating the buoyancy compensator. When releasing the weight belt, care must be taken not to mistake the tank strap for the belt release mechanism and to ensure that the weight belt does not become entangled with other equipment in the drop path.

It is important for the rescuer to be aware of the head position of the victim. It is natural for an anxious or frightened diver to lift his or her head from the water. Because the head is heavy (it weighs about 17 pounds (7.7 kilograms)), it takes a significant effort on the part of the diver to raise it and keep it out of the water. Therefore, if the rescuer can induce the victim to keep the head in the water, the rescue effort will be simplified. Even without using a snorkel or regulator, the rescuer should keep the victim in a head-back position with the nose and mouth clear of the water, because most people can float with little effort if the head is partially or completely submerged.

Once buoyancy and contact have been established, the rescuer may consider removing the victim's mask. This will facilitate breathing, ease some of the psychological stress, and improve eye contact. If the victim is calm, however, the mask can be left on to keep water out of the nose. Generally, it is desirable to remove the backpack and tank to facilitate towing; it is essential to do so when an unassisted long tow is anticipated, if the tow will require passing through kelp, or if exit from the water must be made through surf or rocks. Throughout the process of equipment removal, the procedures followed should be explained and the assistance of the victim obtained, if possible.

19.5.5 Towing a Victim in the Water

After the victim has been stabilized at the surface, the cause of the original incident may still be present. The victim should be checked immediately to see that the face is not in the water, the mask is not pulled down over the mouth, and the airway is clear. The regulator (if functioning properly) may need to be restored to the victim's mouth. In calm water, it may be useful to leave a snorkel in the victim's mouth; however, if the victim is being towed on his or her back, water may enter the snorkel and mouth. The victim is then ready to be transported to a boat, to shore, or to some other type of stable platform.

Towing a victim should not be attempted if the victim is panicky or struggling, or if the safety of the rescuer is otherwise jeopardized. If the victim is conscious and breathing and help is on the way, the rescuer should wait until it arrives before beginning to tow. Distance, chop, swells, current, surf, kelp, and the strength of the rescuer all should be considered.

To tow a victim effectively, the rescuer must remain mobile, which may require the removal of equipment such as the tank or weight belt. The victim's body should be in a position (usually on the back) that will not impede the tow. If the victim does not have a functioning regulator, the face must be out of water, which can best be accomplished by having the buoyancy compensator inflated enough to keep the face out of water.

The rescuer should use a towing technique that allows the victim to be observed. If possible, the rescuer should maintain eye contact with a conscious victim.

Towing with a Line

Whenever possible, a towline or rescue throw bag (see Section 19.4) should be used because it is less fatiguing for the rescuer, reduces the need to ditch equipment, and may permit the rescuer to minimize physical contact with a struggling victim.

A *conscious victim* should grasp the line, which may have a buoyant object attached to it. After grasping the line, the conscious victim should be told to roll over on his or her back to avoid being pulled under during tow. Once the victim has the line and is in position, the tow can be started slowly, because haste could result in pulling the line loose or swamping the victim. If the victim is unconscious, the line should be attached by the rescuer so that it can be detached easily. The line also may be attached to the rescuer as long as it can be released easily. As with a conscious victim, the tow must be slow so as not to swamp the victim. This technique is particularly useful because it permits the rescuer to administer artificial resuscitation easily or to otherwise tend the victim, if necessary.

Tank-Tow Method

Although many towing techniques require physical contact between the victim and rescuer, it is generally recommended that divers learn the tank-tow method. Using this technique, the rescuer grasps the victim's tank with his or her right hand from his or her position at the victim's left side, being sure to maintain visual and verbal contact (see Figure 19-7). This method allows the rescuer to commence mouth-to-mouth resuscitation in the do-si-do position described earlier (see Figure 19-3). It should be kept in mind, however, that although the victim's tank provides a convenient

Figure 19-7
Tank-Tow Method

Reprinted from *Scuba Life Saving*, pub. Royal Life Saving Society, Canada, 1987

handle, towing is faster if the tank is removed. Circumstances such as surface conditions, towing distance, and relative size of rescuer and victim dictate whether equipment should be left intact or dropped. Regardless of these circumstances, both the victim's and the rescuer's tanks must be removed if the tow is through kelp or heavy surf.

Towing with Two Rescuers

Two rescuers may efficiently tow a victim on the surface. After the victim has been placed on his or her back and the weight belt has been removed, buoyancy compensator inflated, and mask and mouthpiece removed, one rescuer is positioned on each side. The rescuer on the victim's right supports the victim's head with the left hand and grasps the victim's elbow or upper arm, using the right hand in a palm-down position. The second rescuer grasps the victim's upper and lower left arm firmly. The tow is made with the rescuers swimming on their backs.

Another method that may be used by two rescuers is to place the victim on the back with a rescuer on each side. Each rescuer grasps a wrist of the victim with the outside hand and places the inside hand on the victim's upper arm or in the armpit. When using this tow, the rescuers swim in a snorkel position.

19.5.6 Leaving the Water with a Victim

Removing the victim from the water may be the most difficult part of a rescue. It can be exceedingly difficult to transport a victim through heavy surf, coral formations, or mud, or to lift a victim onto a pier, dock, or boat. The situation may be complicated further if the victim is in continued need of artificial resuscitation. Regardless of the point of exit, any encumbering equipment belonging to either the victim or the rescuer should be removed before leaving the water. Victims requiring artificial resuscitation should be placed on a flat hard surface as quickly as possible, because CPR cannot be administered in the water.

If the victim is unconscious, the head and chest should be tilted downward during removal from the water; this position will help water drain from the airways. In cases where a back or neck fracture is suspected, care should be taken to avoid any twisting, bending, flexing, or extending of these parts. In such cases the victim should be fastened securely to a back board, with many ties or straps, before being removed from the water. These special precautions should not delay removal of victims from the water if they are not breathing, because CPR must be started as soon as possible. Further details of the techniques for removing a victim from the water may be found in Smith and Allen (1978).

NOTE

When attempting to remove a victim from the water, every effort should be made to obtain help by shouting, lighting flares, using a radio, or any other means at hand.

Into Small Boats. A single rescuer will have considerable difficulty getting an incapacitated diver into a small boat, particularly if the victim is unconscious. If the boat is properly equipped with a ladder (see Section 10.4.2), the rescuer should climb in first and then assist the victim. If there is no ladder, the hands of the victim may have to be secured to the anchor line or some part of the boat to keep the face out of the water while the rescuer climbs in. Once aboard, the rescuer can then untie the victim's hands and pull the victim aboard. If the victim can climb aboard a boat with no ladder, the rescuer's shoulders may be used as a stepping stone. It is important during efforts to get into small boats to keep the victim between the rescuer and the boat, in order to maintain control.

Onto Larger Boats, Piers, and Cliffs. Lifting an incapacitated victim into a boat, onto a high dock, or up a wall or cliff presents a serious problem to a rescuer even if assistants are available. If the boat's gunwale is too high to reach over, a line with a bowline in it may be slipped under the victim's arms, with the knot in the middle of the back. If assistants are available, one or more light lines can be attached to the loop so that the weight of the victim can be divided among the members of the rescue team.

Through Surf. Exiting through the surf with an injured diver is very difficult and exposes both the victim and the rescuer to the possibility of serious injury. As the surf zone is approached from open water, the rescuer must continually watch the approaching waves. Large waves generally come in "sets" or groups of 3 to 6 waves about 10 to 15 seconds apart, with 2 to 3 minutes of smaller waves between sets. It is advisable to leave the surf zone during the lull between sets of larger waves, waiting outside the surf zone for a lull. If the victim is apprehensive or panicky, it may be necessary to pause seaward of the surf zone to calm him or her down.

WARNING

Never Attempt to Tow a Panicky Victim Through Surf to Shore

To permit continued observation of the surf, the rescuer should tow the victim from the back toward shore. If it appears that large breaking waves may catch them, it is advisable to move seaward again to wait for the next lull. As a breaking wave approaches, the rescuer should turn toward shore, hold the victim firmly, cover the victim's mouth and nose, and let the wave strike from behind. Surf often is accompanied by rip currents, and the rescuer must be cautious to avoid being swept seaward (see Section 10.2.3). The use of more than one rescuer is highly desirable when exiting through surf. If two rescuers are available, the victim should be transported with one rescuer on each side towing the victim by the arms. Once ashore, the victim should be treated in accordance with the injuries sustained. A non-breathing victim should be placed on shore as soon as possible and CPR should be started (see Section 18.1.4).

Onto a Rocky Shore. When going from deep water onto an adjacent rock or reef, the rescuer should tow the victim as close to the rocks as possible, then attempt to ride a swell up onto the rock with the buoyant victim turned sideways and held in front of the prone rescuer. The wave may serve as a kind of cushion because the leading edge precedes the body and rebounds back off the rocks, which helps prevent the victim from striking the rocks. The rescuer must brace on the rocks as soon as contact is made and hold on until the water from the swell has receded. The victim then can be rolled higher on the rocks. Once on solid ground, a standard fireman's or shoulder carry can be used to move the victim further inshore. As with other resuscitation techniques, CPR, if needed, should be started as soon as possible.

19.6 ACCIDENT MANAGEMENT

Once the victim has been removed from the water and is on a solid platform such as a boat, pier, or beach, a reassessment of the situation must be made immediately. The first things to check for are life-threatening conditions such as airway obstruction, cessation of breathing, reduced circulation, bleeding, and shock. The examination procedures for each of these are described in detail in Section 18. An unconscious diver should be suspected of suffering from gas embolism and be treated accordingly, unless embolism definitely can be ruled out. Concurrently, every effort should be made to summon outside help, using the telephone, radio, runners, flags, or any means available.

Although cost should not be a factor in the management of a diving accident, it is an important element to keep in mind during planning. Statistics show that costs incurred for treatment of a diving injury can exceed $1,400/day. When added to an expense as great as $10,000 for a jet air ambulance, costs can easily reach $33,000 for a 14-day recompression treatment/hospital stay (Wachholz 1986). For example, the cost for chamber treatment ranges from $100 to more than $300 per hour, depending on the type of chamber, its geographical location, and supporting medical services. The charge for a non-hospital-based chamber will be less than that for a hospital-based chamber. Most chambers charge about $225 per hour (Wachholz 1986). Thus, good planning and accident management practices make sense from a financial point of view.

19.6.1 Summoning Aid

Because many divers and boaters are not familiar with the procedures for summoning aid in emergencies, critical time is lost, causing needless suffering and perhaps even loss of life. The nature of the aid and the procedures to obtain it obviously vary with the situation, e.g., on land in a populated area, on land in a remote area, or at sea. When on land in a populated area, local police, fire, and rescue services should be notified, as in any kind of accident. When on a boat, the best procedure is to seek assistance from the U.S. Coast Guard.

Many signals have been devised over the years to signal distress or other emergency status. The most common, which have been accepted by international agreement or national custom or may be used occasionally by Coast Guard Search and Rescue Units (U.S. Coast Guard 1973), are shown below.

INTERNATIONAL DISTRESS SIGNALS

- A gun or other explosive signal fired at intervals of about a minute.
- A continuous sounding with any fog-signaling apparatus.
- Rockets or shells throwing red stars fired one at a time at short intervals.
- A signal made by radiotelegraphy or by any other signaling method consisting of the group S-O-S in the Morse code.
- A voice signal consisting of the spoken word "Mayday."
- The International Code Signal of distress indicated by the code group NC.
- A signal consisting of a square flag having above or below it a ball or anything resembling a ball.
- Flames on a vessel (as from a burning tar barrel, oil barrel, etc.).
- A rocket parachute flare or a hand flare showing a red light.
- A smoke signal giving off a volume of orange-colored smoke.
- Slowly and repeatedly raising and lowering arms outstretched to each side.
- The radiotelegraph alarm signal, which is designed to actuate the radiotelegraph auto alarms of vessels so fitted, consisting of a series of 12 dashes, sent in 1 minute, the duration of the interval between 2 consecutive dashes being 1 second.
- The radiotelephone alarm signal consisting of 2 tones transmitted alternately over periods of from 30 seconds to 1 minute.

Table 19-2 summarizes the procedures for obtaining emergency aid, evacuation of casualties, and diving medical advice. Only national information has been included because local numbers and procedures vary from location to location and radio call numbers and telephone numbers are changed frequently.

When contact is made by radio or telephone, the caller should declare that the situation is an emergency and state the nature of the emergency. For example, "This is an emergency. I have a diving accident victim needing treatment in a recompression chamber." The caller should be prepared to provide information on the location, including direction and distance from prominent land marks, environmental conditions relating to sea state, roads, wind, etc., and the status of the victim. Unusual circumstances should be described and the number of victims identified. If the victim's location changes, all individuals involved in the rescue should be advised of the new location and of any planned moves or changes.

In 1980, a national Divers Alert Network (DAN) was established at Duke University Medical Center, Durham, North Carolina, as the country's medical advisory service for divers. For administrative purposes, the system is divided into seven regions (see Figure 19-8). Medical help for victims of diving accidents is now available 24 hours a day (Mebane and Dick 1985).

To use DAN, a diver or physician dials (919) 684-8111 and asks for DAN (collect calls are accepted in an emergency). The call is answered by an operator at the Duke University Medical Center. If the call is in regard to an injured diver, the caller is put in contact with a dive physician (one is available 24 hours a day). This physician may advise the caller directly or refer the caller to a local diving physician. If needed, the physician will work with a DAN Regional Coordinator to arrange referral and transport to an appropriate treatment facility. DAN regional coordinators are qualified in diving medicine and know what treatment facilities are available in their regions. In addition, each region has trained medical staff and suitable chambers available continuously (Dick 1982).

Although the Coast Guard does monitor Citizens Band (CB) Channel 9, this is a very unreliable means of communication, for many reasons. If unable to raise the Coast Guard via CB, contact someone else to relay

Table 19-2
Sources of Emergency Assistance

Medical Advice—Nearest Operable Chamber Location

U.S. Navy Experimental Diving Unit
Panama City, Florida (904) 234-4355

Divers Alert Network
Box 3823 - DAN - 215
Duke University Medical Center
Durham, North Carolina 27710
(919) 684-8111

Search, Rescue and Casualty Evacuation

Atlantic SAR Coordinator —	Commander, Atlantic Area U.S. Coast Guard Rescue Coordination Center Governor's Island, NY (212) 668-7055
Pacific SAR Coordinator —	Commander, Pacific Area U.S. Coast Guard Rescue Coordination Center San Francisco, CA (415) 556-5500
Inland SAR Coordinator —	Commander, Aerospace Rescue and Recovery Service U.S. Air Force Rescue Coordination Center Scott Air Force Base, IL (618) 256-4815

Emergency Communications Frequencies

500 kHz	International CW/MCW distress and calling
2182 kHz	International voice distress, safety and calling (particularly useful for communications between aircraft and vessels)
156.8 MHz (ch 16)	FM, U.S. voice distress and international voice safety and calling

Continuous Broadcast NOAA Weather Frequencies

(When weather affects emergency operations)

162.550 MHz
162.400 MHz
162.475 MHz

Derived from NOAA (1979)

messages. If there is no radio on the boat, hail a boat that has a marine band radio and give it the information to relay to the Coast Guard. Keep the boat with you for further contacts. The International Convention for the safety of life at sea requires that assistance be provided to vessels in distress.

If other boats are not immediately available, proceed to the nearest inhabited dock and telephone local paramedic or USCG services. Advise them of a diving accident, state the need for transportation, and give your exact location. Have someone remain at the telephone for further assistance. Ensure that the person on the line is aware that a recompression chamber will be needed.

If symptoms occur on land after diving, contact local paramedics or the USCG. These individuals should be able to assist or give the location of the nearest recompression chamber. If the accident has occurred in a remote area and radio communication is not available, any means at hand should be used to signal the emergency, e.g., smoke, fire, flares, etc. If, under such conditions, help arrives by air but cannot land, the signals shown in Table 19-3 should be used to convey information to the rescuers.

When the rescue aircraft arrives, you should wave and fire flares or smokes, if possible. Let them know you are the one who needs assistance. Do not assume the pilot will recognize you, because valuable time may be wasted searching unnecessarily. In addition to the signals described in Table 19-3, there are a number of miscellaneous signals used for signaling distress; these are shown below.

Figure 19-8
Divers Alert Network (DAN)

MISCELLANEOUS EMERGENCY VISUAL SIGNALS

- Inverted U.S. flag. Used as a distress signal by marine craft in the United States.
- The following are used as a surface-to-air distress recognition signal. When spread horizontally or waved, they indicate that this is the unit in need of assistance:

  —A cloth of international orange color (United States).
  —A cloth of international orange color with a black square and ball inscribed thereon (United States and Canada).
  —A cloth of red color (Caribbean territories).
  —Green fluorescent dye marker.
  —Flashes (as from a signal mirror).
  —Smoke from signal fires. Note: Three signal fires arranged in a triangular pattern are a positive signal of distress.

Occasionally, divers in a small boat may be called on to render assistance in an emergency situation. If the emergency call is by radio or telephone, the procedures will be obvious. If, however, a rescue aircraft is seeking assistance from a boat in the area of an emergency, it is important that those in the boat understand some simple air-to-surface signals. The maneuvers used in this situation by the U.S. Coast Guard Search and Rescue system are described below.

INTERNATIONAL AIRCRAFT TO SURFACE CRAFT SIGNALS

The following maneuvers performed in sequence by an aircraft means that the aircraft wishes to direct a surface craft toward an aircraft or a surface craft in distress:

- Circling the surface craft at least once
- Crossing the projected course of the surface craft close ahead at low altitude and:

  —rocking the wings
  —opening and closing the throttle
  —changing the propeller pitch
- Heading in the direction in which the surface craft is to be directed.

The following maneuver by an aircraft means that the assistance of the surface craft is no longer required:

- Crossing the wake of the surface craft close astern at a low altitude and:
  —rocking the wings
  —opening and closing the throttle
  —changing the propeller pitch.

NOTE

Opening and closing the throttle and changing the propeller pitch are alternative signals to rocking the wings.

19.6.2 On-Site Care of the Diving Casualty

A major problem with divers is that they tend to ignore mild symptoms of decompression sickness that may develop into a more serious problem later on. Detailed descriptions of the symptoms of decompression sickness are provided in Section 3.2.3.2. Section 20.10.1 gives treatment procedures. If there is no hyperbaric chamber on site, divers suspected of having serious decompression sickness and who are not having breathing problems should be administered oxygen immediately and be placed on the left side in a head downward position (modified Trendelenberg Position) with the head at least 19 inches (48.3 centimeters) lower than the feet, as shown in Figure 19-9. This position is not recommended for victims requiring CPR or those with breathing problems. In these cases, it is recommended that a flat supine position be used (Mebane and Dick 1985). The patient should then be transferred immmediately to the nearest hyperbaric chamber. If the symptoms are relieved within 10 minutes, the patient should be kept on oxygen for a total of 30 minutes. If the symptoms get worse, follow the recommendations of the flowchart shown in Figure 19-10. An excellent source of accident management and on-site patient care is the DAN Underwater Diving Accident Manual (Mebane and Dick 1985).

Table 19-3
Ground-to-Air Visual Signal Code

No.	Message	Code Symbol	No.	Message	Code Symbol
1	Require doctor—serious injuries	|	10	Will attempt take-off	|>
2	Require medical supplies	| |	11	Aircraft seriously damaged	⌊⌉
3	Unable to proceed	X	12	Probably safe to land here	△
4	Require food and water	F	13	Require fuel and oil	L
5	Require firearms and ammunition	︾	14	All well	LL
6	Require map and compass	□	15	No	N
7	Require signal lamp with battery and radio	¦	16	Yes	Y
8	Indicate direction to proceed	K	17	Not understood	JL
9	Am proceeding in this direction	↑	18	Require engineer	W

Source: U.S. Coast Guard (1973)

WARNING

The Trendelenberg Position Should Not Be Used if Airway Is Blocked or CPR Is Needed

A common problem in the management of diving cases is that such cases are often misdiagnosed initially, either by divers at the scene or by a physician untrained in diving medicine. To minimize the likelihood of overlooking serious symptoms of decompression sickness or gas embolism, an attending physician should give a neurological examination before, during, and after treatment. Such an examination usually takes about 30 minutes and requires certain diagnostic equipment and training to interpret the results.

Since a physician is rarely at the scene of a diving accident, however, a preliminary 4-minute neurological evaluation has been developed that requires no equipment and can be administered by non-medical persons. This examination is shown below, and a checklist for recording examination results is shown in Table 19-4.

INITIAL NEUROLOGICAL EXAMINATION TO BE ADMINISTERED BY NON-MEDICAL PERSONNEL

NOTE

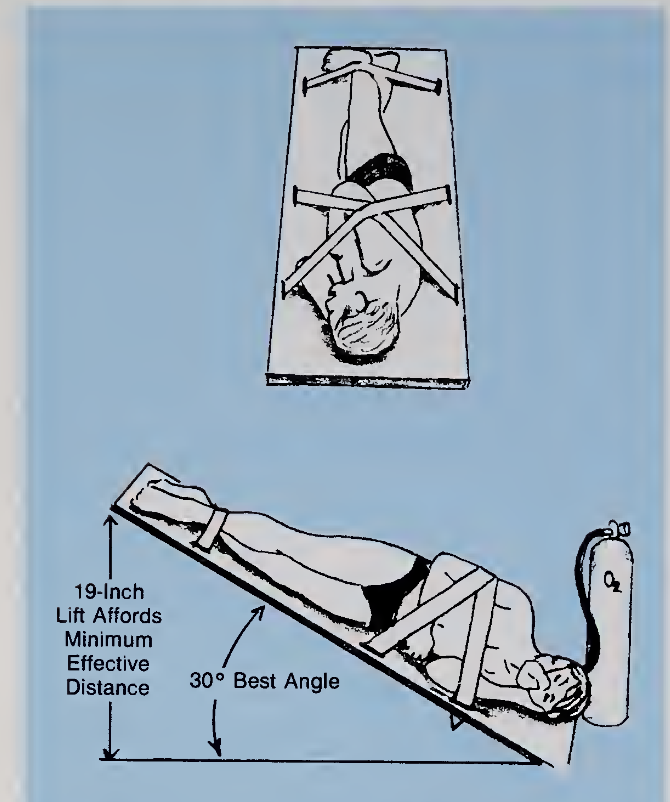
When interpreting the results of this examination, be sure that abnormalities are a result of the diving disorder and not the result of a previous disorder, e.g., some divers may have a hearing impairment caused by working around loud equipment.

Mental Condition or Status

Since less interference is required to impair functioning of the higher mental faculties, test for subtle signs of serious decompression sickness by observing:

- Orientation
  - —Time (the first function to go). Example: "What day is this?"
  - —Place (the next to go). Example: "Where are you?"

Figure 19-9
Modified Trendelenberg Position



Strap victim in place but do not interfere with respiration

Administer 100 percent oxygen if available

Derived from Rutkowski (1985) and Mebane and Dick (1985)

—Person (severe impairment). Example: "What is your name?"

- Memory
  —Immediate (test with a number series).
  —Recent (happenings within last 24 hours).
  —Remote (background).
- Mental function
  —Test by using serial 7's. (Subtract 7 from 100, then 7 from the answer, and so on. If an error is repeated, like "93, 90, 83, 80, 73, 70," a condition called perseveration exists, which usually indicates impairment.
- Level of consciousness
  —Watch for any fluctuation.
- Seizures
  —These are readily apparent.

Cranial Nerves

What to check and how to test 12 cranial nerves, if possible. Test one side vs. the other side.

- Sense of smell (Olfactory nerves)
  —Test with coffee, one nostril at a time. Do not delay for this test if appropriate testing material is not available.
- Sight (Optic nerves)
  —Hold up fingers for the patient to count; test one eye at a time.
- Eye movement (Oculomotor, Trochlear, and Abducens nerves)
  —Have the patient's eyes follow your finger as you move it up and down, left and right.
- Chewing (Trigeminal nerves)
  —Can the teeth be clenched? Feel jaw muscles on both sides simultaneously.
- Mouth (Facial nerves)
  —Can the patient smile?
  —Can both corners of the mouth be lifted simultaneously?
- Hearing (Acoustic nerves)
  —Test one ear at a time by whispering or rubbing your fingers together approximately 1 inch away from the ear.
- Talking (Glossopharyngeal, Vagus nerves)
  —Check for gagging and proper enunciation.
- Shoulder muscles (Spinal Accessory nerves)
  —Have patient shrug the shoulders while you press down on them. Note any unilateral weakness.
- Tongue (Hypoglossal nerves)
  —Can the patient stick the tongue out (not to one side)?

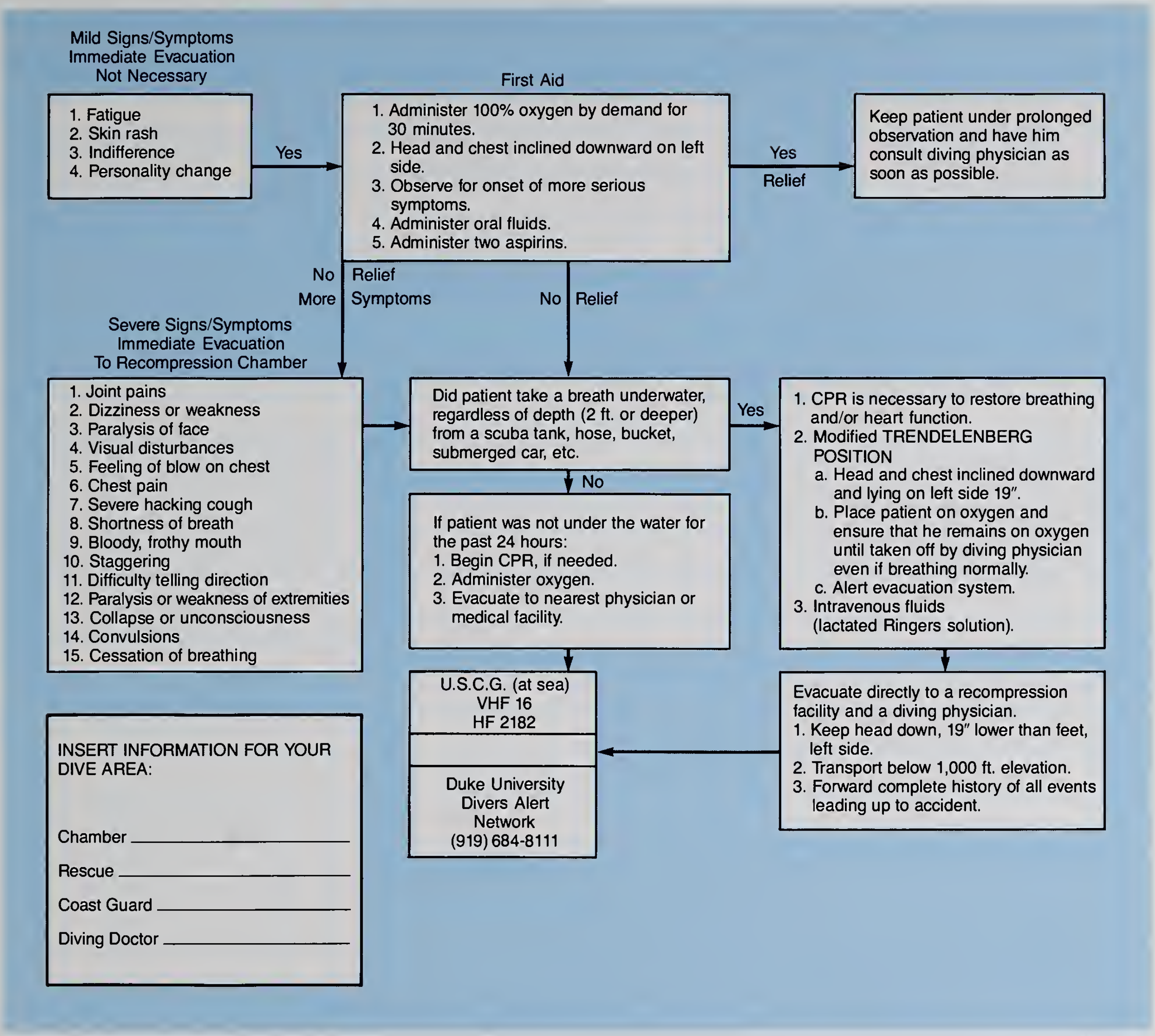
Sensory Nerves

- Sharp vs. dull (check one hand vs. other)
  —Using sharp and dull objects, see if patient can distinguish between them by testing:
  1. Back of hand
  2. Base of thumb
  3. Base of little finger

Motor Nerves

- Muscle strength
  —Have patient grip two of your fingers with each hand. Is the strength the same in each hand?
  —With patient sitting or lying down, place your hands on the legs just above the ankle and press down lightly. Have the patient try to lift the legs. Is the strength equal in both?
- Range of motion
  —Check normal movement of both arms and legs.

Figure 19-10
Diving Accident Management Flow Chart



Mild Signs/Symptoms
Immediate Evacuation
Not Necessary

1. Fatigue
2. Skin rash
3. Indifference
4. Personality change

First Aid

1. Administer 100% oxygen by demand for 30 minutes.
2. Head and chest inclined downward on left side.
3. Observe for onset of more serious symptoms.
4. Administer oral fluids.
5. Administer two aspirins.

Keep patient under prolonged observation and have him consult diving physician as soon as possible.

Severe Signs/Symptoms
Immediate Evacuation
To Recompression Chamber

1. Joint pains
2. Dizziness or weakness
3. Paralysis of face
4. Visual disturbances
5. Feeling of blow on chest
6. Chest pain
7. Severe hacking cough
8. Shortness of breath
9. Bloody, frothy mouth
10. Staggering
11. Difficulty telling direction
12. Paralysis or weakness of extremities
13. Collapse or unconsciousness
14. Convulsions
15. Cessation of breathing

Did patient take a breath underwater, regardless of depth (2 ft. or deeper) from a scuba tank, hose, bucket, submerged car, etc.

If patient was not under the water for the past 24 hours:
1. Begin CPR, if needed.
2. Administer oxygen.
3. Evacuate to nearest physician or medical facility.

1. CPR is necessary to restore breathing and/or heart function.
2. Modified TRENDELENBERG POSITION
   a. Head and chest inclined downward and lying on left side 19″.
   b. Place patient on oxygen and ensure that he remains on oxygen until taken off by diving physician even if breathing normally.
   c. Alert evacuation system.
3. Intravenous fluids (lactated Ringers solution).

Evacuate directly to a recompression facility and a diving physician.
1. Keep head down, 19″ lower than feet, left side.
2. Transport below 1,000 ft. elevation.
3. Forward complete history of all events leading up to accident.

U.S.C.G. (at sea)
VHF 16
HF 2182

Duke University
Divers Alert
Network
(919) 684-8111

INSERT INFORMATION FOR YOUR DIVE AREA:

Chamber ____________________

Rescue ____________________

Coast Guard ____________________

Diving Doctor ____________________

Source: Rutkowski (1985)

- Muscle tone
  —Check if muscles are spastic (in state of contraction) or flaccid (totally relaxed).

Coordination (Cerebellar function)

- Point in space
  —Can patient touch your finger held in front of his or her nose?
- Finger to nose
  —Can the patient touch the tip of his or her nose after touching the tip of your finger?
- Gait
  —Walking gait—check for rubber legs, staggering, and unsteadiness.
  —Tandem gait—walking heel to toe.
- Balance (sharpened Romberg)
  —Have patient stand straight, feet together, arms folded in front and eyes closed.
- Basic reflexes (check both sides with blunt instrument)
  —Biceps
  —Triceps

Table 19-4
Diving Casualty Examination Checklist

Patient ________________ Date ________

LIFE-THREATENING CONDITIONS

1. Airway ________________
2. Breathing ________________
3. Circulation ________________
4. Hemorrhage ________________
5. Shock ________________

MENTAL CONDITION OR STATUS

1. Orientation: Time ________
Place ________
Person ________
2. Memory: Immediate ________
Recent ________
Remote ________
3. Mental function ________
4. Level of consciousness ________
5. Seizures ________

CRANIAL NERVES

1. Sense of smell (Olfactory) R ____ L ____
2. Sight (Optic) R ____ L ____
3. Eye movement (Oculomotor, Trochlear, Abducens) R ____ L ____
4. Chewing (Trigeminal) R ____ L ____
5. Mouth, smile (Facial) R ____ L ____
6. Hearing (Acoustic) R ____ L ____
7. Talking (Glossopharyngeal, Vagus) R ____ L ____
8. Shoulders (Spinal Accessory) R ____ L ____
9. Tongue (Hypoglossal) R ____ L ____

SENSORY NERVES

1. Sharp vs. Dull R ____ L ____

MOTOR NERVES

1. Muscle strength R ____ L ____
2. Range of motion R ____ L ____
3. Muscle tone R ____ L ____

COORDINATION

1. Point in space R ____ L ____
2. Finger to nose R ____ L ____
3. Gait: Walking ________
Tandem ________
4. Balance ________

REFLEXES

1. Basic: Biceps R ____ L ____
Triceps R ____ L ____
Forearm R ____ L ____
Knee R ____ L ____
Ankle R ____ L ____
2. Babinski reflex R ____ L ____

LANGUAGE

1. Aphasia ________

Comments or conclusions ________________

Examiner ________________

Source: NOAA (1979)

—Forearm
—Knee
—Ankle

Reflexes

- Babinski reflex
  —Run a blunt object up the sole of the foot. If the toes curl down toward the sole of the foot, a normal Babinski is present. If nothing happens, no conclusion can be drawn, but if the toes flex backward, upward, and spread, this is a reliable sign of probable spinal involvement.

Language Problem

- Aphasia (Speech impairment)
  —Check for language foulups like misplaced words and incorrect word order.

The results of this examination should be communicated to a consulting physician if a physician is not on site or should be given directly to an attending physician at the first opportunity.

19.7 EVACUATION BY AIR

Each helicopter evacuation presents unique problems. Knowing what to expect and the procedures to follow, however, can save time, effort, and perhaps a life. The following information is applicable to U.S. Coast Guard (USCG) helicopter evacuation by sea, but the same rules also apply to most helicopter evacuations.

- Try to establish communications with the helicopter. If your boat does not have the necessary frequency, try to work through another boat.
- Maintain speed of 10 to 15 knots (5 to 7.5 m/s); do not slow down or stop.
- Maintain course into wind about 20 degrees on port bow.
- Put all antennas down, if possible without losing communications.
- Secure all loose objects on or around the decks, because the helicopter will create strong winds.
- Make sure the patient is ready in advance of the transfer, because time is critical both to the victim and the hovering aircraft.
- Signal the helicopter pilot when all is ready, using hand signals by day and flashlight at night (see Figure 19-11).
- If a trail line is dropped by the aircraft, guide the basket to the deck with the line.
- To prevent electric shock, allow the lifting device (stretcher) to touch the boat before handling it.
- Do not secure any lines/wires from the boat to the basket.
- Place a personal flotation device on the patient.
- Tie the patient in the basket, face up.
- If the patient cannot communicate, attach personal information such as name, age, address, what happened, and what medication has been administered.
- If the patient is a diving accident victim, ensure that the flight crew has a copy of, or is instructed in, medical procedures for diving accidents.
- If the patient is a diving accident victim, ensure that the flight crew delivers the patient to a hyperbaric trauma center (recompression chamber complex).
- If the patient dies, inform members of the flight crew so they do not take unnecessary risks.
- Helicopter transfers should not be made if the victim is being given cardiopulmonary resuscitation, because the chest compression should not be stopped for the time needed to lift the victim. In addition, the helicopter crew may not include an individual trained in CPR.

Figure 19-11
Evacuation by Helicopter

Photo Wayne Marshall

WARNING

Do Not Secure a Trail Line, Basket, or Cable from the Aircraft to the Boat. To Prevent Electric Shock, Always Allow the Lifting Device (Stretcher) To Touch the Boat Before Handling It

19.8 GUIDELINES FOR EMERGENCY EVACUATION

Regardless of the means of evacuation, certain factors must be followed to minimize additional injury to the patient. These factors include providing the maximum amount of advance information to the rescuing organization and the emergency receiving facility and advising the rescue crew in the proper procedures for transporting a diving casualty.

The following medical evacuation information should be forwarded with the patient. If possible, take time to explain the following steps to the physician or paramedic. Do not assume that they understand the reasons why oxygen should be administered to a diving accident victim. If a patient is breathing normally, a physician may stop the oxygen breathing because he or she does not realize that the patient must continue to breathe oxygen to off-load bubbles. The following steps should be taken:

- Maintain breathing and heart functions; ensure airway remains open.

- Keep patient on 100 percent oxygen delivered by demand valve and incline head downward, left side down, during transportation (see Figure 19-8).
- Ensure paramedics/physicians understand why head down, left side, on 100 percent oxygen by demand is required until patient arrives at chamber.
- Ensure that paramedics and physicians understand why the patient needs to be taken to a recompression chamber instead of a hospital.
- Do not stop giving oxygen to a diving accident patient even if patient is breathing normally, unless there is a need to reopen the airway or the patient shows signs of oxygen convulsions (see Section 3.3). Without oxygen, bubbles will reload with nitrogen and cause increasing symptoms.
- Keep patient out of the hot sun and watch for shock.
- Do not give any pain-killing drugs (including aspirin); intravenous injections can be given to prevent vascular collapse or dehydration.
- Instruct flight crews to fly or pressurize aircraft below 800 feet (244 meters) (see Section 14.8).
- Provided the aircraft can handle the extra weight, the diving buddy should be transported with the patient, because he or she also may need recompression or can provide information, comfort, and contact with patient's relatives.
- A complete history of all events leading up to the accident and evacuation must be forwarded with the patient.
- Depth gauges, tanks, regulators, and other diving equipment should be forwarded with patient if weight limitations allow, especially if the accident was fatal. If this is not possible, they should be maintained in the condition in which they were found, pending any accident investigation.

Once the patient arrives at the emergency treatment facility, the procedures described in Section 20 should be followed.

19.9 ACCIDENT REPORTING PROCEDURES

All diving accidents involving NOAA personnel, whether fatal or non-fatal, must be reported promptly. The procedures for reporting accidents are contained in the NOAA Diving Regulations. In addition, all diving accidents should be reported to the National Underwater Accident Data Center, University of Rhode Island, P.O. Box 68, Kingston, RI 02881. The telephone number is (401) 792-2980.

Accidents, both fatal and non-fatal, also should be reported to DAN (see Section 19.6.1). In addition to providing medical advice in diving emergencies, DAN serves as a clearinghouse for information on diving accidents and their treatment. Information (without identifying data) is collected on the victims to be studied on a national level. It is then made available to those participating groups, such as certifying agencies and equipment manufacturers, who are responsible for training and equipping divers (Dick 1982).

Reporting accidents is more than a legal responsibility; it permits an investigation and compilation of accident statistics. From this information, all concerned can learn to improve diving techniques, which will result in fewer diving accidents in the future.

SECTION 20
DIAGNOSIS AND TREATMENT OF DIVING CASUALTIES

DIAGNOSIS AND TREATMENT OF DIVING CASUALTIES

20

20.0 GENERAL

This chapter covers the diagnosis and treatment of a variety of diving- and pressure-related conditions that may occur during diving operations. These conditions range from relatively minor (otitis externa) to life-threatening (Type II decompression sickness, arterial gas embolism). The on-site treatment of injuries is addressed in Section 18, Emergency Medical Care.

20.1 PHYSIOLOGIC AND PATHOLOGIC EFFECTS OF DIVING GASES

The presence or use of air and other gases under pressure is accompanied by a variety of adverse physiological effects, ranging from carbon dioxide poisoning to nitrogen narcosis. This section describes the symptoms and signs associated with these effects, the conditions under which they are likely to occur, and the appropriate forms of treatment.

20.1.1 Carbon Dioxide Poisoning

Carbon dioxide (CO_2) buildup (or excess) often occurs when divers work hard and their lung ventilation does not increase enough to vent off the CO_2 produced by their exertion. Scuba divers who skip-breathe often experience CO_2 buildup. Carbon dioxide poisoning may also occur when a faulty rebreather causes a buildup of CO_2 in the diving mask or helmet.

Symptoms and Signs

Occasionally, CO_2 poisoning produces no symptoms, although it is usually accompanied by an overwhelming urge to breathe and noticeable air starvation. There may be headache, dizziness, weakness, perspiration, nausea, a slowing of responses, confusion, clumsiness, flushed skin, and unconsciousness. In extreme cases, muscle twitching and convulsions may occur.

Treatment

Divers who are aware that they are experiencing carbon dioxide buildup should stop, rest, breathe, and ventilate themselves and their apparatus. Fresh breathing gas usually relieves all symptoms quickly, although any headache caused by the buildup may persist even after surfacing. If a diver becomes unconscious, he or she should be treated in accordance with the procedures described in Section 20.6.

20.1.2 Hypoxia

When the tissues do not have enough oxygen to maintain normal function, the condition is called hypoxia. Hypoxia usually reflects inadequate oxygen in the gases in the lungs (but see Section 20.1.3 on carbon monoxide). Because an increase in total pressure also increases the partial pressure of the oxygen in the breathing mixture (see Section 2.5.1), a diver breathing a gas mixture with less than 20 percent oxygen can often continue to function normally at depth. However, when the diver begins to ascend, the oxygen partial pressure drops as depth decreases, and the diver may lose consciousness before reaching the surface. Breath-hold divers are particularly at risk, especially if they hyperventilate before diving, because hyperventilation reduces the level of CO_2 in the blood, and it is the blood CO_2 level that provides the principal impetus to take another breath. As a consequence, a diver with a low CO_2 blood level can stay under water longer without discomfort and without experiencing the urge to breathe again. This situation can produce a vicious cycle: in the time it takes for the diver's CO_2 blood level to build up sufficiently to make him or her aware of the need to take another breath, the tissues have used up additional oxygen and the CO_2 tension in the diver's blood has dropped. If the oxygen partial pressure drops below the level necessary to maintain consciousness, the diver loses consciousness.

A similar danger exists when artificial breathing mixtures and rebreathing scuba are being used, because heavy exertion or low gas flow may diminish the concentration of oxygen in the breathing bag. This may continue until a pressure is reached that renders the diver unconscious at depth or until the oxygen partial pressure drops to an inadequate level during ascent.

The victims of hypoxia do not usually understand what is occurring, and they may even experience a feeling of well-being. Hypoxia may be accompanied by an excess of carbon dioxide in the blood (see Section 20.1.1).

Symptoms and Signs

- Frequently none (the diver may simply lapse into sudden unconsciousness)
- Mental changes similar to those of alcohol intoxication
- Confusion, clumsiness, slowing of response
- Foolish behavior
- Cyanosis (bluish discoloration of the lips, nailbeds, and skin)
- In severe cases, cessation of breathing.

Prevention

- Avoid excessive hyperventilation before a breath-hold dive.
- When diving with rebreathing scuba, flush the breathing bag with fresh gas mixture before ascending.

Treatment

- Get the victim to the surface and into fresh air.
- If under water and using a rebreather, manually add oxygen to the breathing circuit.
- If the victim is still breathing, supplying a breathing gas with sufficient oxygen usually causes a rapid reversal of symptoms.
- An unconscious victim should be treated as if he or she is suffering from gas embolism (see Section 20.4.2).
- Cardiopulmonary resuscitation should be administered if necessary and should be continued after the victim is in the recompression chamber.

20.1.3 Carbon Monoxide Poisoning

When carbon monoxide (CO) is absorbed, it prevents the blood from transporting oxygen, causing tissue hypoxia even when there is adequate oxygen in the lungs. During treatment, this tissue hypoxia must be overcome by administering higher concentrations of oxygen, and the toxic CO must be eliminated by supplying the diver with CO-free breathing gas. The most frequent cause of carbon monoxide in a diver's air supply is that exhaust fumes from the compressor have entered the compressor's air intake. As the total pressure increases with depth (see Section 3.1.3.4), very slight amounts of carbon monoxide in the diver's breathing gas can have toxic effects.

Symptoms and Signs

Carbon monoxide poisoning usually produces no symptoms until the victim loses consciousness. Some victims experience headache, nausea, dizziness, weakness, a feeling of tightness in the head, confusion, or clumsiness, while others may be unresponsive or display poor judgment. Rapid deep breathing may progress to cessation of breathing. There may be abnormal redness or blueness of lips, nailbeds, or skin. The classic sign of CO poisoning, "cherry-red" lips, may or may not occur and is therefore not a reliable diagnostic aid.

Treatment

The victim should be given fresh air and, if available, oxygen. Some effects, such as headache or nausea, may persist after the exposure has ended. An unconscious victim should be treated in accordance with the procedures outlined in Section 20.6. If a recompression chamber is available, the victim should be treated using U.S. Navy Treatment Table 5 or 6 (see Appendix C).

20.1.4 Asphyxia

Asphyxia (or suffocation) occurs when the lung is unable to carry out the function of ventilation. In diving, this situation could be the result of blockage of the windpipe or gas supply hose or the breathing of an irrespirable gas mixture (too little oxygen or too much carbon dioxide). Drowning is a special case of asphyxiation.

The signs and symptoms of asphyxia and the treatment for it are the same as those for hypoxia and carbon dioxide poisoning. For instructions on the treatment of blocked airway, see Section 18.2.

20.1.5 High Pressure Oxygen Poisoning

Oxygen poisoning is the direct result of breathing pure oxygen or excessive oxygen under pressure. It is most likely to occur when closed-circuit scuba is being used and the depth for which the gas was mixed has been exceeded. If not treated promptly, oxygen poisoning can cause death.

Symptoms and Signs

- Restlessness
- Tingling sensation of the finger tips, lips, and nose
- Tunnel vision
- Ringing in the ears
- Twitching of the face
- Nausea
- Dizziness

- Difficult breathing
- Anxiety and confusion
- Unusual fatigue
- Clumsiness
- Grand mal seizure.

Before the onset of a seizure, the only sign likely to be noticed is twitching of the facial muscles. Consciousness is lost at the onset of the seizure. Shortly thereafter, breathing usually stops. Violent seizures generally continue for a minute or two; biting the tongue and various physical injuries may occur during seizures. Breathing generally resumes spontaneously after a seizure, but the victim may remain unconscious for several minutes afterward and may be drowsy or confused after consciousness is regained.

Treatment

In dives where the oxygen level is high, oxygen poisoning should be suspected if any of the symptoms or signs listed above is noticed. Steps to decrease the oxygen partial pressure should be taken as soon as one or more of these signs or symptoms occurs. If a diver exhibits one of the signs or symptoms while in a dry chamber, the oxygen breathing mask should be removed and the diver should breathe chamber air. Because an increase in CO_2 can trigger oxygen toxicity, the diver should breathe deeply to ventilate CO_2 from the lungs. If a diver using rebreathing circuit scuba shows signs of incipient oxygen poisoning, he or she should flush the breathing bag with fresh breathing gas.

Oxygen-induced seizures generally stop before any treatment can begin. Those treating the victim should concentrate on preventing the victim from injuring himself or herself or from drowning. Because of the risk of breath-holding and air embolism, the pressure (depth) should not be changed while a diver is convulsing. If normal breathing does not resume, cardiopulmonary resuscitation should be administered. If a convulsing diver surfaces, there is reason to suspect an air embolism; the diver should be recompressed and treated immediately (see Section 20.4.6).

20.1.6 Inert Gas Narcosis

Narcosis is a state of stupor or unconsciousness that is caused in diving by breathing inert gases at pressure. Inert gases vary in their narcotic potency, and they may interact with each other to produce effects greater than those produced individually. Nitrogen narcosis, which is caused by breathing compressed air at depth, is the most common form of narcosis encountered in diving. The effects of narcosis may be noticed even at depths barely exceeding 100 fsw (30.5 m), but the symptoms become more pronounced at depths greater than 150 fsw (47 m). Inert gas narcosis produces a sensation of apprehension, confusion, impaired judgment, and a false sense of well-being. The ability to concentrate or even to perform simple tasks is difficult. Divers may do things they normally would not attempt (removing their regulator, swimming to unsafe depths without regard for decompression sickness or the duration of their air supply). By forcing themselves to concentrate on the task at hand, experienced divers can keep narcotic effects under some control, but even they may be unaware of the decrement in their performance under these conditions.

Symptoms and Signs

- Loss of judgment and skill
- A false feeling of well-being
- Lack of concern for job or safety
- Apparent stupidity
- Inappropriate laughter.

Treatment

There is no specific treatment for nitrogen narcosis. A diver experiencing narcosis must be brought to a shallower depth, where the effects will gradually wear off.

20.2 EAR PROBLEMS IN DIVING

The common signs and symptoms of ear injury are a sensation of ear fullness, pain, hearing loss, noise in the ear (tinnitus), or vertigo. The conditions leading to ear problems and the consequences of these problems are described below.

20.2.1 Ear Fullness

Ear fullness, or a sensation that the ears are blocked, is usually the result of a condition that causes a decrease in the transmission of sound to the inner ear. On the surface, ear fullness occurs when the external ear canal is completely blocked with wax or other material. With upper respiratory tract illnesses, ear fullness may be the result of fluid that has been secreted into the cavity of the middle ear and that has not been able to drain out through the eustachian tube. In diving, failing to keep the pressure in the middle ear equalized when the external pressure increases during descent may cause middle ear squeeze and be accompanied by fluid or blood in the middle ear and a consequent feeling of ear fullness (see Section 20.3.2). Divers may find it difficult or impossible to equalize the pressure in their ears during an episode of upper respiratory tract infection or hay fever because of the swelling of the throat tissues, which blocks the opening of the eustachian tubes.

The best way to avoid ear fullness in diving is to maintain the ear canal in a clean and open condition. In addition, divers should not dive when they have an upper respiratory tract infection or are suffering from hay fever or other allergic symptoms.

20.2.2 Hearing Loss

Hearing loss is classified in three categories:

(1) Conductive hearing loss, which is caused by dysfunction of any component of the sound conduction system, such as complete occlusion of the external auditory canal by wax, inflammation, swelling of the ear drum or lining of the middle ear, fluids in the middle ear, changes in middle ear gas densities, pressure gradients across the ear drum, fixation of the ear bones, or loss of elasticity of the ear drum caused by scarring, large perforations, or interruption of the ear bones.

(2) Neurosensory or nerve hearing loss, which is caused by occlusion of the blood supply to the inner ear, head injury, stroke, bubbles, leakage of inner ear fluids from a round or oval window rupture, excessive noise exposure, or various other inner ear diseases or conditions.

(3) Mixed or combined conductive and neurosensory hearing losses, which are caused by simultaneous dysfunction of the middle and inner ear.

20.2.3 Tinnitus

Tinnitus (spontaneous noise or ringing in the ear) can occur with the type of middle ear disease that causes a conductive hearing loss. However, this condition is usually associated with inner ear or brain disease.

20.2.4 True Vertigo

True vertigo is a disorder of spatial orientation that is characterized by a sense that either the individual or his or her surroundings are rotating. Injury to the vestibular system that results in vertigo is frequently associated with nausea, vomiting, visual disturbance, fainting, and generalized sweating. Vertigo is the most hazardous ear symptom in diving. When it is caused by inner ear dysfunction, it may be accompanied by ear pain, hearing loss, or tinnitus. Vertigo can result from cold water entering the external ear canal, unequal ear clearing during ascent or descent, inner ear barotrauma, ear drum rupture, or injury to the central nervous system. Once a diver has experienced dizziness during diving, he or she should be examined by a specialist in diving medicine before attempting further diving.

20.2.5 Alternobaric Vertigo

Unequal or asymmetrical clearing of the middle ear during descent or ascent, and particularly during ascent, can cause vertigo. Regardless of the cause, vertigo and its accompanying spatial disorientation are hazardous if they occur during a dive.

Treatment

The best treatment for alternobaric vertigo is prevention. First, individuals should not dive if they have difficulty clearing their ears or if a Valsalva maneuver on the surface produces vertigo. Second, if a diver notices any vertigo, ear blockage, or ear fullness during compression, he or she should stop any further descent and should ascend until the ears can be cleared. Third, if such symptoms are noted during ascent, the diver should stop and descend until the symptoms disappear (if breathing gas and other conditions permit).

20.2.6 Damage to Inner Ear

The inner ear may be damaged permanently by inadequate pressure equilibration of the middle ear during descent. It is therefore critical that divers equalize the pressure in the middle ear with the external pressure.

Symptoms and Signs

Inner ear injuries are accompanied by vertigo, nerve deafness, and a loud roaring in the involved ear. One or all of these symptoms may be present. Deafness may be total or partial and may occur concurrently with or several days after middle ear barotrauma. Many of these injuries have been associated with forceful attempts, against closed mouth and nose, to clear the ears at depth. This force results in an increase in cerebrospinal fluid pressure, which is transmitted to the fluid in the inner ear spaces, causing an increase in the already negative pressure in the middle ear. The oval window or the thin round window membranes may then bulge into the middle ear and rupture, causing a leak of inner ear fluids into the middle ear. The signs and symptoms of inner ear barotrauma can easily be confused with those of inner ear decompression sickness. Table 20-1 differentiates between these two conditions.

Prevention

Divers should not perform a forceful exhalation against a closed nose and mouth (Valsalva maneuver) to attempt to clear their ears at depth. If ear-clearing cannot be

Table 20-1
Characteristics of Inner Ear Barotrauma and Inner Ear Decompression Sickness

	Inner ear barotrauma	Inner ear decompression sickness
1. Time of symptom onset	During compression (associated with middle ear barotrauma).	During or shortly after decompression.
2. Dive characteristics	Dives not requiring staged decompression.	Dives requiring staged decompression.
	Can occur during compression phase of deeper dives.	Dives without proper, staged ascents.
	Dives with rapid descents.	
	Reported cases associated with air diving—can probably occur with helium diving.	More common during decompression from helium dives—can occur with air diving.
3. Possible associated symptoms	Difficulty with ear clearing and/or ear pain or drainage—frequent. May have history of preexisting nasal, sinus, or middle ear disease.	None or other symptoms of decompression sickness.
4. Possible associated physical findings	Signs of middle ear barotrauma—frequent.	None or other signs of decompression sickness.

Source: Bennett and Elliott (1982), with the permission of Bailliere Tindall Ltd.

performed easily at depth, the diver should ascend until the ears can be cleared, even if this means that the dive must be aborted.

Treatment

Any diver who experiences persistent vertigo, hearing loss, or noise in the ear after a dive should consider the possibility of inner ear barotrauma. Any diver with these symptoms should be placed immediately on bed rest, with the head elevated, and should avoid coughing, nose blowing, or straining. If the dive involved a no-decompression schedule or if the diver noted that symptoms began when he or she had difficulty clearing the ears during compression, inner ear barotrauma of compression is the most likely cause. Recompression therapy should be avoided in these cases, because it would expose the diver to the same pressure change that initially caused the injury. Immediate referral of the patient to a medical specialist in ear, nose, and throat problems is a matter of urgency.

20.2.7 Otitis Externa (Swimmer's Ear)

Exposure to water or humid atmospheres can produce maceration, or softening and wasting, of the skin of the ear canal. The canals itch or feel sore, and, if cleaned or scratched with implements like Q-tips, paper clips, or pencils, the macerated skin is further irritated and may become infected. The resulting condition is called otitis externa. Divers who are exposed to water with a high bacterial count, i.e., polluted water, are at special risk for this infection (see Section 11). Divers who have skin allergies or seborrheic dermatitis are particularly vulnerable and may develop otitis externa from showering or shampooing even when they are not diving or swimming.

Symptoms and Signs

Symptoms include pain, irritation, itching, and burning of the ear canal, sometimes accompanied by thin or serous discharge. Examination shows an inflamed, swollen, and tender external ear canal. As the condition worsens, the surrounding ear and skin become red and the lymph nodes in the neck may also become tender and enlarged. The condition may progress to complete obstruction of the ear canal, abcess, and/or spread of infection into the surrounding tissues.

Prevention

Special ear drops (Domeboro® otic solution) are useful for general prophylaxis in humid and aqueous environments, and they should be used after each exposure (1-2 drops in each ear). If a diver is continuously exposed, as occurs in saturation diving, these ear drops should be used four times a day. Particular attention should be paid to keeping the ear canal dry and to maintaining a slightly acid pH in the secretions on the skin surface. An easy and effective formulation is to add a dropper full of household vinegar to one ounce of rubbing alcohol in a dropper bottle. The alcohol absorbs water in the ear, while the vinegar restores its normal acid pH. Another useful measure is to blow warm dry air from a hair dryer into the ear canal gently after each dive or before putting in ear drops.

WARNING

Do Not Put Otic Solutions Into the Ear if There Is Any Possibility of Ruptured Ear Drum

Treatment

The treatment of otitis externa consists of cleansing the canal, applying specific antibiotic therapy, restoring a more normal acid-base balance to the canal, and relieving the victim's pain. The pain is frequently severe and may require analgesics for relief. Cases with severe pain, significant swelling of the ear canal, and redness or inflammation of the external ear should be referred to a physician for treatment. Less severe cases can be managed by irrigating the auditory canal, using lukewarm tap water, and carefully drying the canal after irrigation. After drying, a mild acid solution, such as Domeboro® otic solution, should be applied. This process should be repeated several times daily. Swimming and diving should cease until the symptoms have cleared completely.

20.3 SQUEEZE OR BAROTRAUMA

The human body automatically adjusts to any change in the pressure of the surrounding environment; it usually does so without the person involved noticing the change. Most of the body is composed of watery tissue that can transmit imposed pressure without deformation, but there are a few areas where this is not true. If the gas pressure within some air-filled cavities of the body, such as the middle ear or the bony sinuses of the skull, is not easily equalized with the surrounding pressure, an individual undergoing even mild pressure changes (such as those that occur when riding an elevator, driving in the mountains, or flying in an airplane) may be aware of the pressure difference. In more severe cases, pain, accompanied by fluid and blood in the middle ears or sinuses, may be the result of a "squeeze" in these areas. Such effects are exaggerated in divers because the water that surrounds them is much denser and heavier than air. The ability of diving equipment automatically to deliver breathing gases that are at the same pressure as the surrounding depth of water makes diving possible, but these compressed gases must infiltrate into all the rigid bony cavities (the middle ear, sinuses, and chest cavity) to equalize the pressure inside, or the resulting deformations will lead to squeeze of these areas.

20.3.1 Face Mask Squeeze

Face mask squeeze is generally caused by failure to admit air into the face mask during descent. It can also occur if surface air pressure is lost and the diver is wearing a surface-supplied mask without a non-return valve. The resulting pressure differential between the air pocket in the semi-rigid mask and the flexible tissues of the face can result in serious tissue damage. The most tender tissues are those covering and surrounding the eyeball and the lining of the eyelids. In serious cases of face mask squeeze, damage to the optic nerve and blindness may occur. This type of squeeze can be avoided entirely by exhaling into the mask during descent or by having a non-return valve on the gas supply line of a surface-supplied full-face mask.

Symptoms and Signs

- Sensation of suction on the face, or of mask being forced into face
- Pain or a squeezing sensation
- Face swollen or bruised
- Whites of eyes bright red.

Treatment

Ice packs should be applied to the damaged tissues and pain relievers should be administered if required. In serious cases, the services of a physician should be obtained.

20.3.2 Middle Ear Squeeze

The most common transient ear problem associated with diving is middle ear squeeze or barotrauma, which is caused by inadequate pressure equalization between the middle ear and the external environment. Most divers have experienced middle ear squeeze at one time or another.

Symptoms and Signs

The symptoms of middle ear squeeze consist initially of pain and a sensation of ear blockage (see Section 20.2.1). Conductive hearing loss is always present but may not be the afflicted diver's primary complaint because of the intense ear pain. Mild tinnitus and vertigo may also occur. If the ear drum ruptures, the pain is usually severe; vertigo may also occur, especially if cold water has entered the ear.

Nasal conditions such as congestion and discharge increase the likelihood of poor eustachian tube function during the dive. However, the absence of predive symptoms does not guarantee that a diver will not develop middle ear barotrauma. Divers who develop symptoms of middle ear barotrauma should discontinue diving immediately and should have their ears examined by a physician.

Treatment

Divers who have difficulty clearing their ears and who are not able to resolve this difficulty quickly (for example by ascending a little way and then gently trying to clear their ears again) should stop diving for the moment. After returning to the surface, they should be examined by a qualified person to determine whether there is fluid or blood in the middle ear behind the eardrum.

Often, returning to the surface is all that is necessary to relieve the symptoms of mild ear squeeze, but it may take a few days for the fluid or blood to drain from or be absorbed from the middle ear cavity. A nasal decongestant spray, nose drops, a mild vasoconstrictor medication, or an antihistamine taken by mouth may help to alleviate eustachian tube blockage and facilitate drainage from the middle ear. Chewing gum, yawning, or swallowing may also help.

If examination reveals that the diver has a rupture of the ear drum, the diver should stay out of the water until the tear has healed, which usually occurs quickly (unless an infection in the ear delays the repair process). To monitor the healing process and take steps to control infection in the damaged ear, any diver with a ruptured ear drum should be seen by a physician.

20.3.3 Round Window Rupture

Round window rupture is most often a result of very forceful attempts to equalize ear pressures. Examination and treatment by an ear, nose, and throat specialist is important to prevent permanent injury in these cases.

Symptoms and Signs

If hearing loss, tinnitus, or vertigo occur in association with a no-decompression dive, barotrauma with round window rupture and inner ear damage should be suspected. These symptoms and signs may indicate a serious condition.

Treatment

Divers who have developed deafness, ringing in the ears, or vertigo during a difficult descent or in a no-decompression dive may have suffered a rupture of the round window in the inner ear and should be referred immediately to an ear, nose, and throat specialist as a medical emergency. If inner ear barotrauma is suspected, recompression therapy should not be attempted, because this therapy exposes the diver to the same pressure differentials that resulted in the initial injury and could thus exacerbate round window and inner ear damage. Figure 20-1 illustrates the structure of the external, middle, and inner ear.

20.3.4 Sinus Squeeze

The sinus cavities are air pockets located within the skull bones that have openings into the nasal passages (see Figure 3-7). These cavities are lined with a mucous membrane. As in middle ear squeeze, sinus squeeze normally is the result of diving with a cold or head congestion. Adequate ventilation and pressure equalization in the paranasal sinuses are important in diving, both in descent and ascent, and depend to a large degree on adequate nasal function. Inflammation and congestion of the nasal mucosa caused by allergies, smoking, chronic irritation from prolonged or excessive use of nose drops, upper respiratory tract infections, or structural deformities of the nose can result in blockage of the paranasal sinus openings. The inability to equalize pressure on descent creates negative relative pressure within the sinus cavity, deforming the mucous membrane and causing swelling, fluid exudation, hemorrhage, and pain. Paranasal sinus barotrauma also may occur during ascent. In this case, the key mechanism is thought to be one-way blockage of the sinus opening by cysts or polyps located within the sinus that allow pressure equalization during descent but not during ascent.

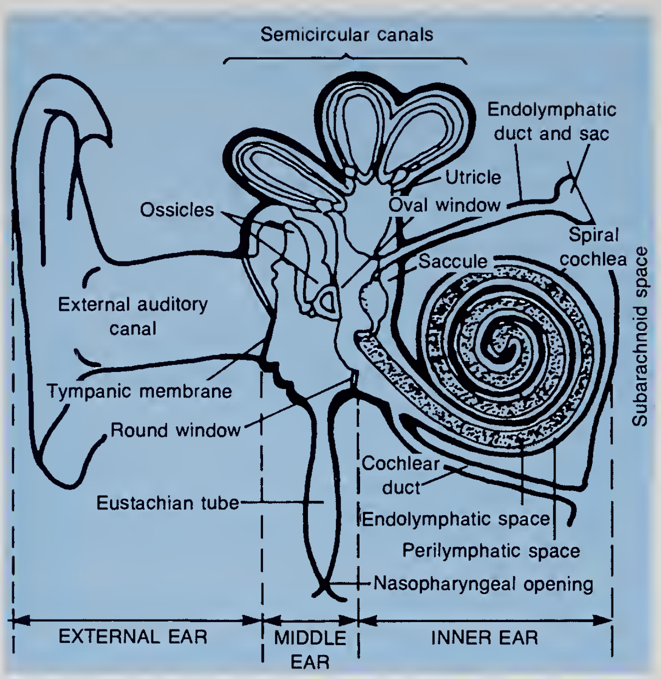
Symptoms and Signs

- Sensation of fullness or pain over the involved sinus or in the upper teeth
- Numbness of the front of the face
- Bleeding from the nose.

Treatment

The treatment of sinus squeeze may involve the use of nose drops, vasoconstrictors, and antihistamines taken by mouth. These medications will promote nasal mucosal shrinkage and opening of the sinus. Most of the symptoms of paranasal sinus barotrauma disappear within 5 to 10 days without serious complications. Divers who

Figure 20-1
Structure of External, Middle, and Inner Ear



The air-containing external auditory canal, middle ear and eustachian tube are noted. The fluid-filled inner ear is subdivided into the perilymphatic and endolymphatic spaces, which connect to the subarachnoid space by the cochlear duct and endolymphatic duct, respectively. Source: Bennett and Elliott (1982), with the permission of Bailliere Tindall Ltd.

have symptoms for longer periods should see a specialist. If severe pain and nasal bleeding are present or if there is a yellow or greenish nasal discharge, with or without fever, a specialist should be seen promptly. Individuals with a history of nasal problems or sinus disease should have a complete otolaryngologic evaluation before beginning to dive.

20.3.5 Lung Squeeze (Thoracic Squeeze)

Lung squeeze is a hazard for the breath-hold diver. It occurs when the ambient pressure rises but there is no corresponding intake of air into the lungs. Tissue damage can result when the size of the lungs has been reduced below the residual volume.

Symptoms and Signs

- Feeling of chest compression during descent
- Pain in the chest
- Difficulty in breathing on return to the surface
- Bloody sputum.

Treatment

In severe cases of lung squeeze, the diver requires assistance to the surface. The diver should be placed face down, and blood should be cleared from the mouth. If breathing has ceased, cardiopulmonary resuscitation with oxygen (if available) should be administered. Attendants should be alert for symptoms of shock, and treatment for shock should be instituted, if necessary. A physician should be summoned as quickly as possible.

20.3.6 External Ear Squeeze

External ear squeeze is related to blockage of the external ear canal during descent or ascent. Such blockage causes ear canal pressure to be negative relative to both ambient and middle ear pressure, which causes damage to the tympanic membrane (ear drum) and some swelling of the lining of the external auditory canal. The common causes of external ear canal obstruction are wax or other foreign bodies, mechanical ear plugs, or a tight-fitting diving hood.

Symptoms and Signs

- Fullness or pressure in region of the external ear canals
- Pain
- Blood or fluid from external ear
- Rupture of ear drum.

Prevention

- Use of solid ear plugs should be prohibited in diving
- Fit of diving hoods and earphones should be adjusted so that they do not completely cover or seal the external ear canal during ascent or descent
- Accumulated wax that can obstruct the ear canal should be removed by gently irrigating the canal with a lukewarm water solution, using a rubber bulb syringe. Care should be taken before irrigation to guarantee that there is no ear drum perforation behind the obstructing wax.

Treatment

Ear drum rupture should be treated according to the procedures for treating middle ear barotrauma. These procedures are described above, in Section 20.3.2.

20.4 DECOMPRESSION SICKNESS AND GAS EMBOLISM

The only adequate treatment for decompression sickness or gas embolism in divers is recompression in a recompression chamber. However, all of the pain a diver experiences after a dive may not be the result of decompression sickness, and other causes should be kept in mind. Generally, however, if symptoms of decompression sickness or gas embolism are observed, it is prudent to initiate recompression treatment rather than to delay. If it cannot be determined whether the diver has serious decompression sickness or gas embolism, the treatment for gas embolism should be chosen; the correct diagnosis is often not made until after the events of the dive have been reviewed with the patient. (See Figure 20-2 for a comparison of the symptoms and signs of decompression sickness and gas embolism.) Although immediate recompression is not a matter of life and death with pain-only bends (as it is in central nervous system decompression sickness or gas embolism), there is a relationship between the speed with which the patient is recompressed and the rate of recovery and avoidance of permanent damage.

Divers can help to reduce the incidence of decompression sickness by knowing and following established limits for depth and time at depth. The hazard of flying at altitudes as low as 1220 meters (4000 feet) even after safe depth-time dives should also be recognized (see Section 14.8).

20.4.1 Decompression Sickness

Decompression sickness, also known as caisson disease or compressed air illness, is the result of inadequate decompression after an exposure to increased pressures. (See Section 3.2.3.2 for a detailed description of decompression sickness symptoms.) The condition is classified in two categories: Type I or pain-only bends, and Type II or central nervous system bends.

20.4.1.1 Decompression Sickness—Pain Only

Type I decompression sickness usually occurs within 6 hours after a dive but may occasionally be diagnosed as long as 24 to 48 hours after surfacing. The signs and symptoms of pain-only decompression sickness are described below.

Symptoms and Signs

- Local pain, usually in joints of arms or legs
- Pain made worse by exercise
- Itching
- Blotchy skin rash.

Immediate Action

- Perform quick neurological examination before recompression to ensure that case is pain only
- Put patient on oxygen (if possible)
- Enter chamber, put patient on oxygen, initiate recompression on appropriate treatment table
- Examine patient thoroughly.

Treatment

Directions for the treatment of pain-only decompression sickness are presented in Section 20.4.5, the list of U.S. Navy Treatment Tables in Table 20-2, the decompression sickness treatment flowchart (Figure 20-3), and in Appendix C.

20.4.1.2 Decompression Sickness—Serious Symptoms

The onset of Type II or central nervous system (CNS) decompression sickness usually occurs within 6 hours of surfacing. The signs and symptoms and treatment of this condition are described below.

Symptoms and Signs

- Dizziness
- Ringing in ears
- Difficulty in seeing
- Shortness of breath
- Rapid breathing
- Choking
- Severe pain
- Pain in abdomen
- Extreme fatigue
- Loss of sensation (numbness)
- Weakness of extremities
- Staggering
- Paralysis
- Collapse or unconsciousness.

Immediate Action

- Institute cardiopulmonary resuscitation, if necessary
- Administer oxygen
- Start immediate recompression on appropriate treatment table
- Perform physical examination, including a neurological examination, as soon as patient's situation permits
- Provide additional life support measures
- Repeat, and complete, physical examination when patient is at treatment depth in recompression chamber.

Treatment

For treatment procedures, see Section 20.4.6, the list of U.S. Navy Treatment Tables in Table 20-2, the decompression sickness treatment flowchart (Figure 20-3), and in Appendix C.

20.4.2 Gas (Air) Embolism

A gas embolism occurs when a bubble of gas (or air) causes a blockage of the blood supply to the heart,

Figure 20-2
Summary of Decompression Sickness and Gas Embolism Symptoms and Signs

DIAGNOSIS OF DECOMPRESSION SICKNESS AND GAS EMBOLISM

	DECOMPRESSION SICKNESS				GAS EMBOLISM			
			SERIOUS		CNS SYMPTOMS			
SYMPTOMS AND SIGNS	Skin	Pain-Only	CNS	Chokes	Brain Damage	Spinal Cord Damage	Pneumo-thorax	Mediastinal Emphysema
Pain-head					■			
Pain-back			□					
Pain-neck								■
Pain-chest			□	■		□	■	□
Pain-stomach			■			□		
Pain-arms/legs		■				□		
Pain-shoulders		■				□		
Pain-hips		■				□		
Unconsciousness			■	□	■	□	□	
Shock			■	□	■	□	□	
Vertigo			■					
Visual difficulty			■		■			
Nausea/vomiting			■		■			
Hearing difficulty			■		■			
Speech difficulty			■		■			
Balance lack			■		■			
Numbness	□		■		■	□		□
Weakness		□	■		■	□		
Strange sensations	□		■		■	□		
Swollen neck								■
Short of breath			□	■	□	□	□	□
Cyanosis				□	□	□	□	□
Skin changes	■							

■ Probable
□ Possible

CONFIRMING INFORMATION

Diving History

	Yes	No
Decompression obligation?	☐	☐
Decompression adequate?	☐	☐
Blow-up?	☐	☐
Breath-hold?	☐	☐
Non-pressure-cause?	☐	☐
Previous exposure?	☐	☐

Patient examination

	Yes	No
Does diver feel well?	☐	☐
Does diver look and act normal?	☐	☐
Does diver have normal strength?	☐	☐
Are diver's sensations normal?	☐	☐
Are diver's eyes normal?	☐	☐
Are diver's reflexes normal?	☐	☐
Is diver's pulse rate normal?	☐	☐
Is diver's gait normal?	☐	☐
Is diver's hearing normal?	☐	☐
Is diver's coordination normal?	☐	☐
Is diver's balance normal?	☐	☐
Does the diver feel nauseated?	☐	☐

Source: US Navy (1985)

Table 20-2
List of U.S. Navy
Recompression Treatment Tables

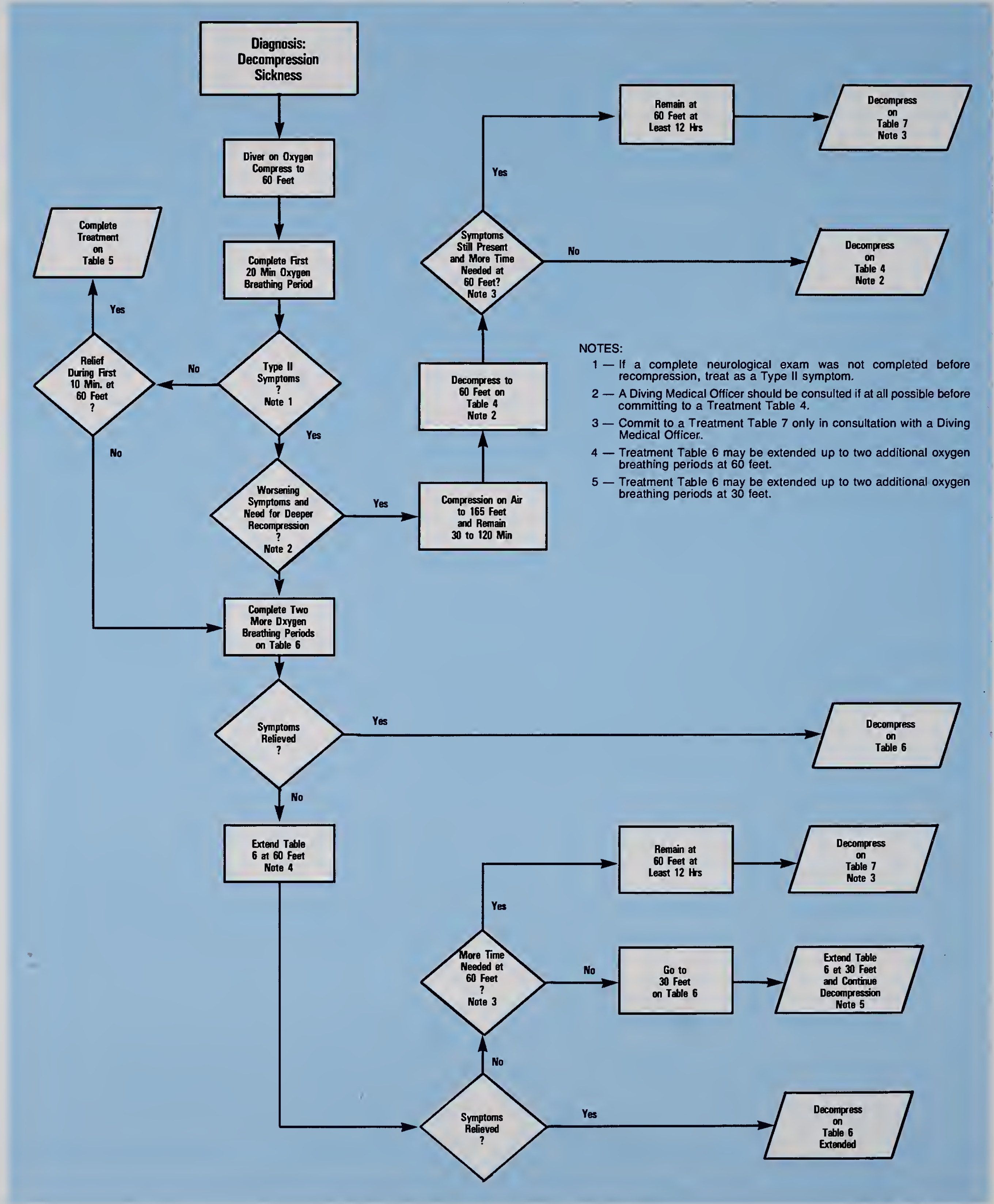
TABLE		USE
TABLES USED WHEN OXYGEN AVAILABLE		
4	Air/Oxygen Treatment of Type II Decompression Sickness or Gas Embolism	Treatment of worsening symptoms during the first 20-min oxygen breathing period at 60 feet on Table 6 or unresolved arterial gas embolism symptoms after 30 min at 165 feet.
5	Oxygen Treatment of Type I Decompression Sickness	Treatment of Type I decompression sickness when symptoms are relieved within 10 minutes at 60 feet and a complete neurological exam was done and is normal.
6	Oxygen Treatment of Type II Decompression Sickness	Treatment of Type II decompression sickness or Type I decompression sickness when symptoms are not relieved within 10 minutes at 60 feet.
6A	Air and Oxygen Treatment of Gas Embolism	Treatment of gas embolism symptoms relieved within 30 min at 165 feet. Use also when unable to determine whether symptoms are caused by gas embolism or severe decompression sickness.
7	Air and Oxygen Treatment of Life Threatening or Extremely Serious Symptoms	Treatment of unresolved severe symptoms at 60 feet after initial treatment on Table 6, 6A or 4. Used only in consultation with a Diving Medical Officer.
TABLES USED WHEN OXYGEN NOT AVAILABLE		
1A	Air Treatment of Type I Decompression Sickness—100-foot Treatment	Treatment of Type I decompression sickness when oxygen unavailable and pain is relieved at a depth greater than 66 feet.
2A	Air Treatment of Type I Decompression Sickness—165-foot Treatment	Treatment of Type I decompression sickness when oxygen unavailable and pain is relieved at a depth greater than 66 feet.
3	Air Treatment of Type II Decompression Sickness or Gas Embolism	Treatment of Type II symptoms or gas embolism when oxygen unavailable and symptoms are relieved within 30 min at 165 feet.
4	Air Treatment of Type II Decompression Sickness or Gas Embolism	Treatment of symptoms which are not relieved within 30 min at 165 feet using Air Treatment Table 3.

NOTE: 1 Always use Oxygen Treatment Tables when oxygen available.
2 Helium-oxygen may be used in lieu of air on these treatment tables upon the recommendation of a Diving Medical Officer.

Source: US Navy (1985)

brain, or other vital tissue. The bubble tends to increase in size as the pressure decreases (Boyle's Law), which makes the blockage worse. (A more complete discussion of gas embolism is given in Section 3.2.2.4.) When divers hold their breath or have local air trapped in their lungs during ascent, the pressure-volume relationships discussed above can occur. Alveoli can rupture or air can be forced across apparently intact alveoli. If air bubbles enter the pulmonary veins, they are swept to the left side of the heart and pumped out into the aorta. Bubbles can enter the coronary arteries supplying the heart muscle, but they are more commonly swept up the carotid arteries to embolize the brain. As the bubbles pass into smaller arteries, they reach a point where they can move no further, and here they stop circulation. Symptoms of gas embolism usually occur immediately or within 5 minutes after surfacing. One, a few, or all of the symptoms listed below may be

Figure 20-3
Decompression Sickness Treatment From Diving or Altitude Exposures



NOTES:

1 — If a complete neurological exam was not completed before recompression, treat as a Type II symptom.

2 — A Diving Medical Officer should be consulted if at all possible before committing to a Treatment Table 4.

3 — Commit to a Treatment Table 7 only in consultation with a Diving Medical Officer.

4 — Treatment Table 6 may be extended up to two additional oxygen breathing periods at 60 feet.

5 — Treatment Table 6 may be extended up to two additional oxygen breathing periods at 30 feet.

Source: US Navy (1985)

present. Prompt recompression is the only treatment for gas embolism. Patients should be treated in accordance with appropriate U.S. Navy Treatment Tables (see Figure 20-4), or the tables in Appendix C.

WARNING

Gas Embolism Is An Absolute Medical Emergency and Requires Immediate Treatment

Symptoms and Signs

- Chest pain
- Cough or shortness of breath
- Bloody, frothy sputum
- Headache
- Visual disturbances such as blurring
- Blindness, partial or complete
- Numbness and tingling
- Weakness or paralysis
- Loss of sensation over part of body
- Dizziness
- Confusion
- Sudden unconsciousness (usually immediately after surfacing but sometimes before surfacing)
- Cessation of breathing.

Immediate Action

- Institute cardiopulmonary resuscitation, if necessary
- Administer oxygen
- Start immediate recompression
- Perform physical examination, including a neurological examination, as soon as situation permits
- Provide additional life support measures
- Repeat, and complete, physical examination when patient is at treatment depth in recompression.

Treatment

Rescuers and attendants must be aware that most embolism victims are also near-drowning victims. Positioning the patient with the head low, in the left side position, is recommended, but trying to position the patient should not be allowed to interfere with the immediate administration of CPR. If available, 100 percent oxygen should be administered, and the patient should be moved as rapidly as possible to a recompression chamber that has a 6-ATA pressure capability. A gas embolism case is a minute-to-minute emergency transfer. The chances of full recovery decrease with each minute lost in returning the patient to pressure. If air transportation is required, the patient must not be exposed to decreased cabin pressure during transit; consequently, aircraft capable of being pressurized to sea level must be used. If a helicopter or unpressurized aircraft is used, the cabin pressure must not be allowed to exceed a few hundred feet of altitude (see Section 14.9). The patient should be transported as rapidly as possible to the nearest adequate recompression facility. Despite the decreased chance of recovery if therapy is delayed, patients have responded even after several hours' delay. Victims should *not* be taken back into the water for treatment.

20.4.3 Omitted Decompression

In situations such as blow-up, loss of air supply, bodily injury, or other emergencies, a diver may be required to surface prematurely, without taking the required decompression. If a diver has omitted the required decompression and shows any symptom of gas embolism or decompression sickness after surfacing, immediate treatment using the appropriate treatment table should be instituted. Treatment in a recompression chamber is essential for these omitted decompression accidents.

Even if the diver shows no ill effects from omitted decompression, immediate recompression is essential. The diver should be compressed to the depth appropriate for the table selected (USN Table 5 or 1A or any other appropriate Appendix C recompression table). If no ill effects are evident, the diver should then be decompressed in accordance with the appropriate treatment table. Any decompression sickness developing during or after this procedure should be considered a recurrence (see Section 20.4.7).

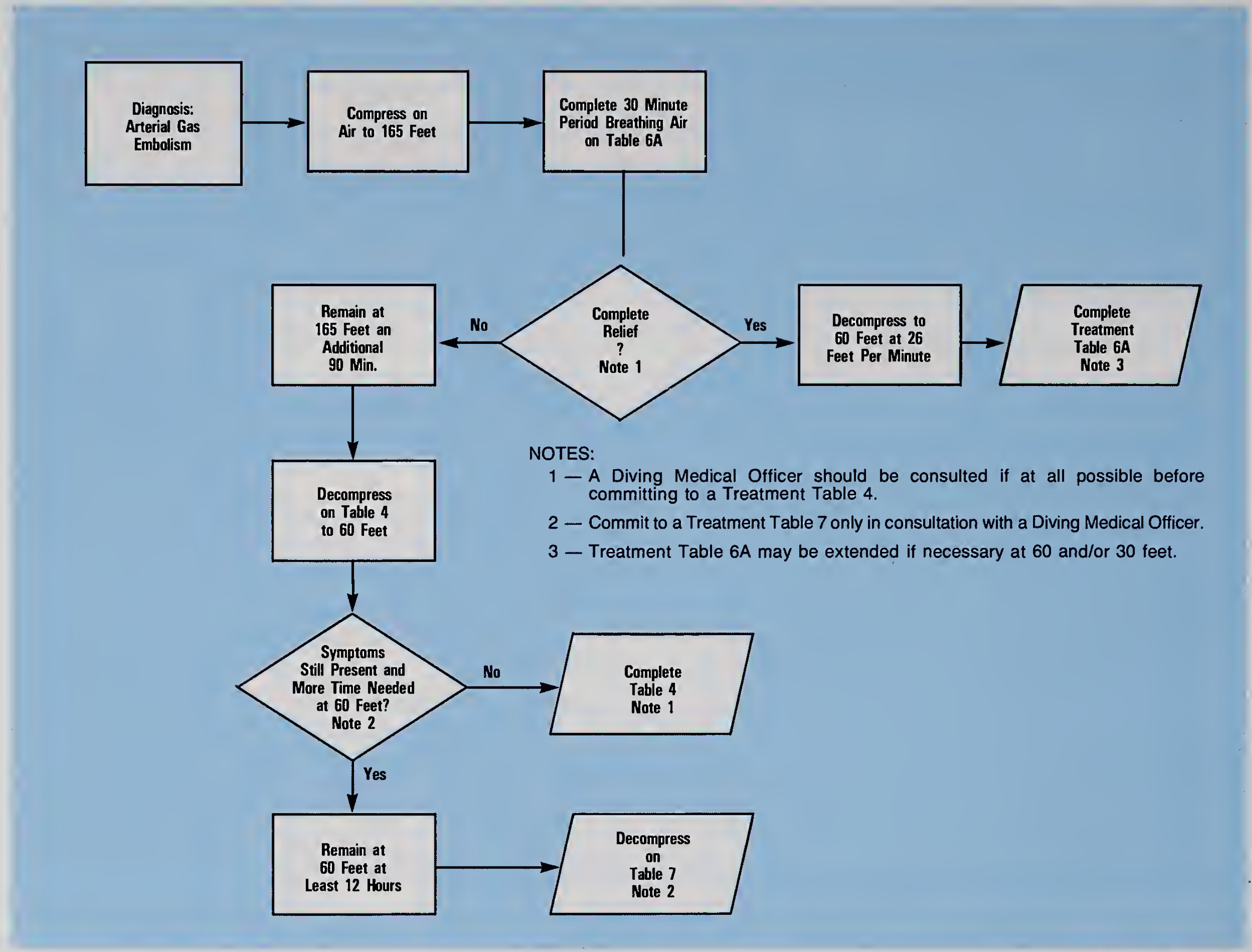
NOTE

The procedure for in-water treatment for omitted, asymptomatic decompression is described in Appendix B and Section 14.8. This procedure should be used only if no recompression chamber is available.

20.4.4 Pretreatment Procedures

Patients may arrive at a chamber in almost any condition: they may have only a mild ache in a joint or they may be comatose. In the best of circumstances, the patient will arrive at the treatment chamber in a pressurized, transportable chamber that is capable of being mated to the treatment chamber. (For a summary of patient handling procedures, see Table 20-3.) In all instances, a rapid examination must be made to determine the condition of the patient. To establish a baseline, the patient is examined at ground level, before the chamber is pressurized. When signs of gas embo-

Figure 20-4
Treatment of Arterial
Gas Embolism



NOTES:

1 — A Diving Medical Officer should be consulted if at all possible before committing to a Treatment Table 4.

2 — Commit to a Treatment Table 7 only in consultation with a Diving Medical Officer.

3 — Treatment Table 6A may be extended if necessary at 60 and/or 30 feet.

Source: US Navy (1985)

lism are present, the patient must immediately be pressurized to 165 fsw (see Figure 20-4). To determine which treatment table to use and to gauge the success of the treatment, this examination is repeated on reaching treatment depth and thereafter. The minimum examination must include:

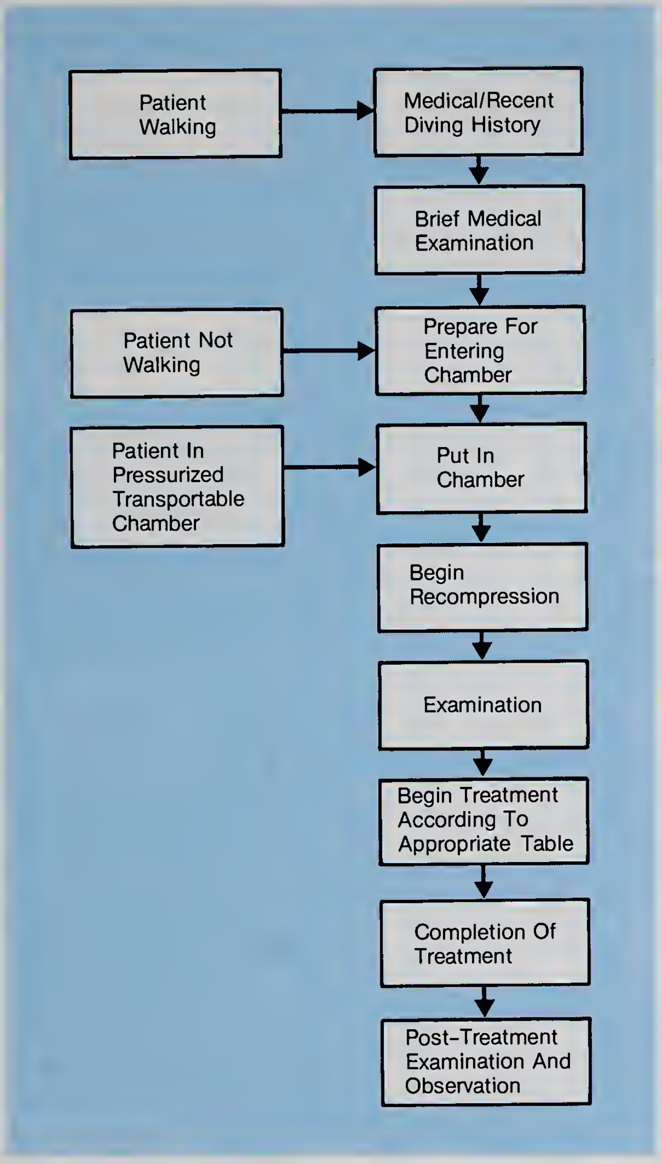
- A discussion with the patient to determine the cause of the accident, how the patient feels, and his or her level of alertness
- Testing of the patient's:
  —Blood pressure
  —Pulse and respiration rates
  —Eyesight
  —Hearing
  —Reflexes
  —Muscular coordination
  —Strength
  —Balance
  —Response to pinprick.

For further information on the preliminary examination of victims suffering from hyperbaric-related accidents, see Section 19.6.2.

20.4.5 Tending the Patient

When a recompression treatment is conducted for pain-only decompression sickness, an experienced physician or diving medical technician should tend the patient inside the chamber. The inside tender must be familiar with all treatment procedures and with the signs, symptoms, and treatment of diving-related injuries and illnesses. If it is known before the treatment begins that specialized medical aid must be administered to the patient, or if a gas embolism is suspected, a physician should accompany the patient inside the chamber. If

Table 20-3
General Patient
Handling Procedures



the chamber is sufficiently large, a second tender may also enter the chamber to assist during treatment. Inside the chamber, the tender ensures that the patient is lying down and positioned to permit free blood circulation to all limbs. During any treatment, the inside tender must remain alert for symptoms of oxygen toxicity. These symptoms can be remembered with the aid of the acronym V-E-N-T-I-D, which derives from:

- VISION, which may include any abnormality, such as tunnel vision (a contraction of the normal field of vision, as if looking through a tube)
- EARS, which may include any abnormality of hearing
- NAUSEA, which may be intermittent
- TWITCHING, which usually appears first in the lips or other facial muscles but may affect any muscle. (This is the most frequent and clearest warning of oxygen poisoning.)
- IRRITABILITY, which includes any change in behavior, such as anxiety, confusion, and unusual fatigue
- DIZZINESS, which may additionally include symptoms such as difficulty in taking a full breath, an apparent increase in breathing resistance, noticeable clumsiness, or lack of coordination.

20.4.6 Treatment Tables

The primary treatment for decompression sickness is recompression. Recompression tables developed by many different agencies and organizations are available. These include USN Treatment Tables 1A, 2A, 3, 4, 5, 6, 6A, and 7; Figure 20-3 summarizes the use of these tables. The NOAA Diving Safety Board recommends a number of recompression procedures for treating diving accidents; these tables are shown in Appendix C, along with an Accident Treatment Flowchart to be followed when selecting a treatment strategy. The first step in any treatment involves diagnosing the condition properly. Figure 20-2 is a diagnostic aid designed to ensure the selection of an appropriate table. Once a treatment table has been chosen, treatment is conducted by carrying out the recompression procedures specified for that table (see Figures 20-3, 20-4, and Appendix C). If complications occur during or after treatment, the procedures shown in Figure 20-5 and Appendix C apply.

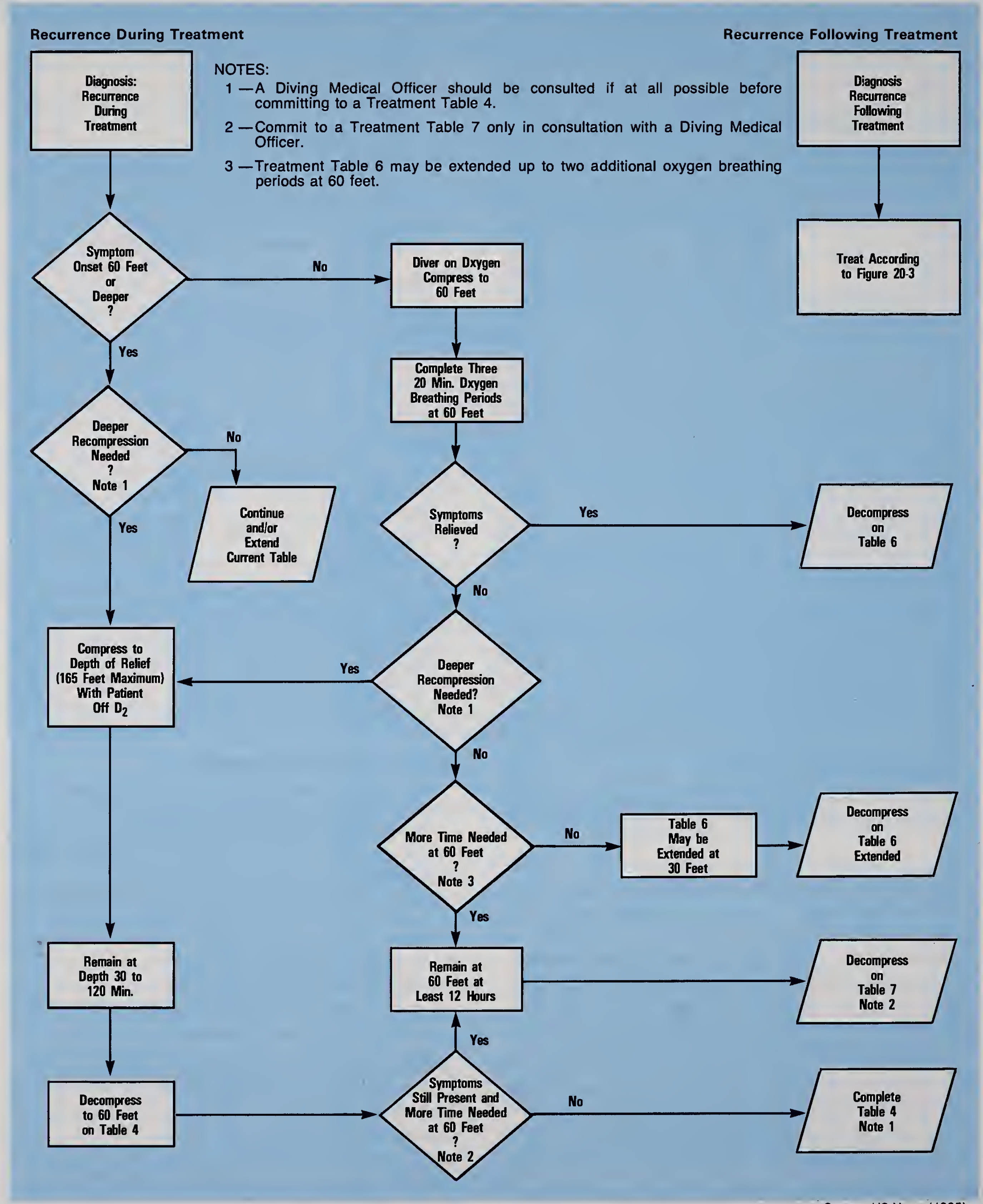
20.4.7 Failures of Treatment

Four major complications may affect the recompression treatment of a patient. These are:

- Worsening of the patient's condition during treatment
- Recurrence of the patient's original symptoms or development of new symptoms during treatment
- Recurrence of the patient's original symptoms or development of new symptoms after treatment
- Failure of symptoms of decompression sickness or gas embolism to resolve despite all efforts using standard treatment procedures.

When any of these complications occurs, the advice of diving medicine experts should be sought immediately, because alternative treatment procedures have been developed and used successfully when standard treatment procedures have failed. These special procedures may involve the use of saturation diving decompression schedules; cases of this type occur more frequently

Figure 20-5
Treatment of Symptom Recurrence



NOTES:
1 —A Diving Medical Officer should be consulted if at all possible before committing to a Treatment Table 4.
2 —Commit to a Treatment Table 7 only in consultation with a Diving Medical Officer.
3 —Treatment Table 6 may be extended up to two additional oxygen breathing periods at 60 feet.

Source: US Navy (1985)

when a significant period of time has elapsed between the onset of symptoms and the initial recompression. Although it is important to know that alternative procedures are available, it is equally important to note that they have not been standardized. It is therefore essential that the advice of experts in the field of hyperbaric medicine be obtained as soon as there are indications that the standard treatment procedures are not alleviating the symptoms. The use of an oxygen-nitrogen saturation therapy may be the only course of action when the situation involves a paralyzed diver already at depth whose condition is deteriorating.

20.5 OTHER LUNG OVERPRESSURIZATION ACCIDENTS

In addition to gas embolism, several other types of lung overpressurization accidents may occur under diving conditions. These accidents include pneumothorax, mediastinal emphysema, and subcutaneous emphysema.

20.5.1 Pneumothorax

Pneumothorax is the result of air escaping from within the lung into the space between the lungs and the inner wall of the chest cavity. As the air continues to expand, there is partial or total collapse of the lung. In serious cases, the heart may be displaced and the blood circulation may be diminished or stopped.

Symptoms and Signs

- Sudden onset of cough
- Shortness of breath
- Sharp pain in the chest, usually made worse by breathing
- Swelling of neck veins
- Blueness (cyanosis) of skin, lips, and nailbeds
- Pain in chest, evidenced by grimacing or clutching of chest
- A tendency to bend the chest toward the side involved
- Rapid, shallow breathing
- Irregular pulse.

Treatment

First aid treatment of pneumothorax consists of administering oxygen. Unless air embolism is present, recompression is not indicated. If breathing is impaired seriously and no physician is available to vent the pleural cavity with a chest tube or large needle, the victim should be recompressed to the point of relief. A qualified individual must then be locked into the chamber to insert a chest tube before decompression is possible.

20.5.2 Mediastinal Emphysema

Mediastinal emphysema (air within the chest in the tissues between the lungs and the heart) may result from rupture of a pleural bleb or injury to the lung, esophagus, trachea, or mainstem of the bronchus. Although not in itself serious, mediastinal emphysema demonstrates that the lung has been overpressurized, and close examination for the symptoms or signs of gas embolism is therefore required.

Symptoms and Signs

- Pain under the breastbone that may radiate to the neck, collarbone, or shoulder
- Shortness of breath
- Faintness
- Blueness (cyanosis) of the skin, lips, or nailbeds
- Difficulty in breathing
- Shock
- Swelling around the neck
- A brassy quality to the voice
- A sensation of pressure on the windpipe
- Cough.

Treatment

Unless gas embolism is also present, recompression is not necessary for mediastinal emphysema. Medical assistance should be obtained and oxygen administered, if necessary.

20.5.3 Subcutaneous Emphysema

Subcutaneous emphysema has the same cause as other lung overpressurization accidents but is not nearly so serious. This condition results when air escaping from the lung migrates out of the thorax into the subcutaneous tissues (just under the skin), usually in the area of the neck, collarbone, and upper chest. The two conditions of subcutaneous and mediastinal emphysema are often associated with one another, and the signs of the two conditions may overlap.

Symptoms and Signs

- Feeling of fullness in the neck area
- Swelling or inflation around the neck and upper chest
- Crackling sensation when skin is moved
- Change in sound of voice
- Cough.

Treatment

Unless complicated by gas embolism, recompression is not necessary. The services of a physician should be obtained and oxygen should be administered if breathing is impaired.

20.6 MANAGEMENT OF THE UNCONSCIOUS DIVER

When divers retrieved from the water are unconscious or collapse soon after surfacing, they should be treated for gas embolism unless another cause is clearly indicated (see Section 20.4.2). The many possible causes of unconsciousness include: gas embolism, decompression sickness, cardiac arrest, carbon monoxide poisoning, head injury, near-drowning, convulsion, insulin reaction (in a diabetic on insulin), or hyperventilation or hypoventilation. Regardless of the cause, the immediate priority if the patient is not breathing is cardiopulmonary resuscitation. Clearing of the airway, mouth-to-mouth ventilation, and closed-chest heart massage may also be required (see Sections 18.3 and 18.4). Because the unconsciousness must be assumed to have been caused by an embolism, the diver must be transported immediately to a recompression chamber. During transportation, the diver should be positioned, if possible, with the head low and the body lying on the left side. Cardiopulmonary resuscitation should be continued if necessary, and supplemental oxygen should be administered if it is available. Resuscitation should continue until the victim recovers or is pronounced dead by a physician. Prompt recompression is necessary for an unconscious diver under all conditions except these two:

- Gas embolism or decompression sickness has been completely ruled out.
- Another lifesaving measure that makes recompression impossible, such as a thoracotomy, is essential.

20.7 PERSONNEL REQUIREMENTS FOR CHAMBER OPERATIONS

The minimum team for conducting any recompression operation consists of a diving supervisor, an inside tender, an outside tender and, depending on the circumstances, a diving physician. The responsibilities of each of these team members are described below.

20.7.1 Diving Supervisor

The diving supervisor is in charge of the operation and must be familiar with all phases of chamber operation and treatment procedures. The supervisor must ensure that communication, logging, and all phases of treatment are carried out according to prescribed procedures.

20.7.2 Inside Tender

The inside tender, who must be familiar with the diagnosis of diving-related injuries and illnesses, monitors and cares for the patient during treatment.

Other responsibilities of the inside tender include:

- Releasing the door latches (dogs) after a seal is made
- Communicating with outside personnel
- Providing first aid as required by the patient
- Administering oxygen or helium-oxygen to the patient
- Providing normal assistance to the patient as required
- Ensuring that ear protection sound attenuators are worn during compression and ventilation
- Maintaining a clean chamber and transferring body waste as required.

During the early phases of treatment, the inside tender must constantly watch for signs of relief of the patient's symptoms. The patient should not be given drugs that will mask the signs of sickness. Observing these signs is the principal method of diagnosing the patient's condition, and the depth and time of symptom relief determine the treatment table to be used. The final decision as to which treatment table to use must be made by the diving supervisor on the recommendation of the attending physician.

20.7.3 Outside Tender

The outside tender is responsible for:

- Maintaining and controlling the air supply to the chamber
- Maintaining the oxygen supply to the chamber
- Keeping times on all phases of the treatment (descent, stops, ascent, overall treatment)
- Keeping the dive log
- Communicating with inside personnel
- Decompressing any inside tending personnel leaving the chamber before patient treatment is complete
- Pressurization, ventilation, and exhaust of the chamber
- Operating the medical lock.

20.7.4 Diving Physician

The diving physician is trained in the treatment of diving accidents. Although it may not be possible to have a diving physician present during all treatments, it is essential that the diving supervisor be able to consult by telephone or radio with a diving physician.

When a diver is being recompressed, all attending personnel must work as a team for the benefit of the patient. Whether the inside or the outside tender operates the chamber will be dictated by the availability of qualified personnel and the circumstances of the casualty being treated. If the patient has symptoms of serious decompression sickness or gas embolism, the team will require additional personnel. If the treatment is prolonged, a second team may have to relieve the first. Whenever possible, patients with serious decompression sickness or gas embolism should be accompanied inside the chamber by a diving medical technician or diving physician, but treatment should not be delayed to comply with this recommendation.

Effective recompression treatment requires that all members of the treatment team be thoroughly trained and practiced in their particular duties. It is also advisable to cross-train members to carry out the duties of their teammates.

20.8 PRESSURE AND OXYGEN TOLERANCE TESTS

Some government agencies require their divers or diver-candidates to pass pressure or oxygen tolerance tests, or both, before they are eligible for diver training or annual recertification. Procedures for pressure and oxygen tolerance tests have proven safe in many years of experience with them. The purpose of the oxygen test is to keep those individuals who are susceptible to oxygen poisoning from diving.

20.8.1 Procedures for Pressure and Oxygen Tolerance Tests

Procedures for pressure and oxygen tolerance tests are as follows:

- The candidate must undergo a physical examination by a Diving Medical Officer and be cleared to undergo the tests.
- The candidate and tender enter the recompression chamber and are pressurized to 112 fsw (50 psig) at a rate that can be tolerated by the candidate.
- The chamber is ventilated for one minute at 112 fsw (33 m) to reduce the temperature.
- The chamber is brought to 60 fsw (18 m) at 60 fsw/min (18 m/min).
- Upon arrival at 60 fsw, a new inside tender is locked in and the first tender is placed in the outer lock and decompressed in accordance with the standard air decompression table. If a new inside tender is unavailable, decompress both the candidate and the tender in accordance with the standard air decompression table upon completion of the 30-minute oxygen test. During this time, the candidate remains idle, and the chamber is ventilated at 12.5 acfm for each person on 100 percent oxygen. The tender must constantly monitor the candidate for oxygen toxicity.
- The tender instructs the candidate in the use of the oxygen mask, and the candidate breathes 100 percent oxygen for 30 minutes.
- After 30 minutes, the chamber is depressurized to the surface at a rate of 60 fsw/min (18 m/min).
- All candidates must remain at the chamber site for a minimum of 15 minutes and in the vicinity for 1 hour. Candidates should not fly after this procedure until 12 hours have elapsed.

During pressurization, the candidate must demonstrate the ability to equalize pressure in his or her ears effectively and must otherwise withstand the effects of pressure. During the oxygen tolerance test, if the candidate convulses or exhibits definite preconvulsive signs, i.e., twitching of the muscles of face or limbs, the test is failed and the mask should be removed. In such a case, the test is not to be repeated. If the candidate complains of symptoms such as nausea, tingling, or dizziness during the test, the mask should be removed and the test terminated, but in such a case the test may be repeated at a later date, at the discretion of the diving physician.

20.9 EMERGENCY MEDICAL RESPONSE

In anticipation both of the routine and unusual medical problems that may arise in the course of diving, all diving operations should have a medical emergency response plan. Such a plan should cover assignment of individual responsibilities in an emergency, the location of equipment and supplies necessary for medical treatment, the availability of a trained hyperbaric physician, and procedures for ensuring adequate patient transport to recompression or medical facilities, if required. In addition, emergency kits should be available that can be used at the scene of a diving accident. These kits should contain the equipment and supplies necessary to treat victims of diving accidents and to maintain life support measures until an emergency medical team can arrive, or until transportation to a definitive treatment facility can be arranged.

20.9.1 Medical Equipment and Supplies

Before a diving operation begins, it is important to consider what medical items would be needed in a diving accident. These items should then be sorted into those that can be used in a hyperbaric chamber and those that will be kept at the surface. An excellent way to handle this requirement is to establish medical kits small enough to carry on a diving operation or to take into the recompression facility. One suggestion, in accordance with an emergency response plan, is to place the necessary medical items into three kits, each having a different purpose:

- Diving operations medical kit (first aid)
- Primary medical treatment kit, containing diagnostic and therapeutic equipment to be available when required and to be inside the chamber during all treatments.
- Secondary medical treatment kit, including equipment and medical supplies that need not be immediately available within the chamber but that could be locked in separately when required.

20.9.2 Diving Operations Medical Kit (First Aid)

The following items are recommended for a diving operations medical kit that would be available at all diving sites:

• General:	Number
—Bandaids	50
—Tube of disinfectant (first aid cream)	1
—Aspirin tablets	
—Dramamine®	

- Diagnostic Equipment:
  - —Flashlight
  - —Stethoscope
  - —Otoscope-ophthalmoscope
  - —Sphygmomanometer (aneroid type only)
  - —Thermometer
  - —Reflex hammer
  - —Tuning fork (500, 1000, and 2000 Herz)
  - —Pin and brush for sensory testing
  - —Tongue depressors
  - —Bandage scissors

• Bandages:	
—Topper sponges	6
—Adhesive tape, 1/2", 1", 2" rolls	2 each
—Adhesive compress, 1"	2
—Bandage compress, 4"	2
—Eye dressing packet	2
—Gauze pads, sterile, 4" x 4"	10
—Curlex® roller bandage, 1"	4
—Curlex® roller bandage, 2"	4
—Curlex® roller bandage, 4"	2
—Triangular bandages, 40"	4
—Trauma dressing	2

• Emergency treatment equipment:	
—Oropharyngeal airway, large	1
—Oropharyngeal airway, medium	1
—Oropharyngeal airway, small	1
—Tongue depressor taped and padded as a bite pad in case of seizures	
—Oxygen resuscitator	1
—Resuscitator masks with water-filled rim	
—Flexible rubber suction catheter	
—Plastic non-flexible suction tips (Yankauer® Suction Tip)	
—Asepto® syringe	1
—Tourniquet	1
—Tweezers	1
—Artery forceps (5" and 8")	2
—Splinting boards 4" wide x 12"	2
—Splinting boards 4" wide x 24"	2
—Wire ladder splints	2
—Liquid/crystal cold packs	3
—Blanket.	1

20.9.3 Primary Medical Treatment Kit

The suggested contents for a medical treatment kit to be available in the recompression chamber during every treatment:

- Diagnostic Equipment:
  - —Flashlight
  - —Stethoscope
  - —Otoscope-ophthalmoscope
  - —Sphygmomanometer (aneroid type only)
  - —Thermometer
  - —Reflex hammer
  - —Tuning fork (500, 1000, and 2000 Herz)
  - —Pin and brush for sensory testing
  - —Tongue depressors
- Emergency Airway Equipment:
  - —Large-bore needle and catheter (12 or 14 French) for cricothyroidotomy or relief of tension pneumothorax

- —Small Penrose® drain or Heimlich® valve for adaption to a thoracentesis needle to provide a one-way flow of gas out of the chest
- —Laryngoscope with extra batteries and bulbs
- —Laryngoscope blades
- —Cuffed endotracheal tubes with adaptors (8.0, 8.5, and 9.5 mm)
- —Syringe and sterile water for cuff inflation (10 ml)
- —Malleable stylet (approx. 12" in length)
- —Sterile lubricant
- —Soft rubber suction catheters

- Miscellaneous:
  - —Bandage scissors
  - —Tourniquet
  - —Adhesive tape
  - —Decongestant nasal spray
  - —Decongestant tablets

- Drugs:
  - —5 percent dextrose in lactated Ringers® solution
  - —5 percent dextrose in normal saline
  - —5 percent dextrose in water
  - —Dextran 70 in saline, 500 ml
  - —Normal saline, 500 ml
  - —Atropine for injection
  - —Sodium bicarbonate for injection
  - —Calcium chloride for injection
  - —Dexamethasone for injection
  - —Epinephrine for injection, 1 mg/ml
  - —Lidocaine® for injection
  - —Diphenhydramine hydrochloride for injection
  - —Phenytoin sodium for injection
  - —Codeine tablets, 30 mg
  - —Aspirin tablets, 325 mg
  - —Sterile water for injection
  - —Injection methyl prednisolone (40 mg/ml in 5 ml) or Decadron® shock pack (dexamethasone)
  - —Injection Valium® (10 mg in 2 ml)
  - —Sterets® injection swabs.

When possible, preloaded syringes should be available to avoid the need for venting the vial to prevent implosion during pressure change within the chamber. If necessary, vials can be vented with a needle inserted through the rubber stopper for pressure equalization during descent and ascent, but the sterility of such vials should then be considered to have been violated and the vial should be discarded and replaced.

20.9.4 Secondary Medical Treatment Kit

The following additional medical supplies are recommended for a kit to be kept somewhere near the recompression chamber to ensure that the contents are available to be locked into the chamber when they are needed:

- Drugs:
  - —5 percent dextrose in lactated Ringers® solution
  - —5 percent dextrose in normal saline
  - —5 percent dextrose in water
  - —Dextran 70 in saline, 500 ml
  - —Normal saline, 500 ml

• Intravenous infusion sets	2
• Intravenous infusion extension sets	2

- 3-way stopcocks
- Syringes (2, 5, 10, 30 ml)
- Sterile needles (18, 20, 22 gauge)
- Nasogastric tube
- Catheterization set, urethral
- Myringotomy knife
- Wound closure instrument tray, disposable
- Sterile scalpel and blade assortment
- Assorted suture material
- Surgical soap
- Sterile towels
- Sterile gloves, surgical (sizes 6-8)
- Gauze pads, sterile, 4" x 4"
- Gauze roller bandage, 1" and 2", sterile
- Bandaids
- Cotton balls
- Splints
- Eye patches
- Medicut® cannula.

20.9.5 Use of the Kits

Because conditions on board ship, at land-based diving operations, and at diver training sites differ, the responsible physician should modify the contents of the medical kits to suit the operation's needs. All three kits should be taken to the recompression chamber or scene of the accident. Sterile supplies should be produced in duplicate. Any sterile supplies not sealed adequately against changes in atmospheric pressure should be resterilized after each pressure exposure or, if not exposed in the interim, at 6-month intervals. All drug ampules will not withstand pressure, and bottle stoppers may be pushed in by increased pressure. Bottles with stoppers may be vented with a needle during pressurization and can then be discarded if not used.

The emergency kit should be sealed in such a way that it can be opened readily when needed; the condition of the seal should indicate that it has been opened. Each kit should contain a list of contents, and each time it is opened, the contents should be verified against the inventory and the condition of all items checked.

Use of the primary or secondary medical treatment kits should be restricted to the physician in charge or to a diving medical technician. Concise instructions for administration of each drug should be provided in the kit. In untrained hands, many of these items can be dangerous.

APPENDIX A
DIVING WITH DISABILITIES

DIVING WITH DISABILITIES

A

INTRODUCTION

Increasingly sophisticated scuba equipment and training techniques have made diving accessible to more people. Non-physical attributes such as good judgment, a healthy respect for personal, environmental, and equipment limitations, and constant attention to safety are now considered as important, if not more important, to safe recreational diving than physical strength. In addition, the availability of tanks of various sizes and of suits and equipment designed to fit divers with different physical characteristics has enabled many individuals to dive who do not fit the traditional stereotype. Among these are divers with a variety of disabilities; these divers must accomplish diving tasks using a lesser amount of physical force than is the case for able-bodied divers. The equipment and techniques that these divers with disabilities use minimize the amount of effort required to accomplish a given task—a clear advantage for any diver. Thus all divers can benefit from the techniques developed by divers with disabilities.

There are many types of disabilities: vision, hearing, and speech impairments; disabling conditions caused by diseases such as cerebral palsy, multiple sclerosis, diabetes, and arthritis; brain and other injuries caused by accidents or illnesses; and emotional and learning disabilities. This appendix is concerned with orthopedic disabilities, i.e., those that make standing, walking, climbing ladders, or negotiating sandy beaches in dive gear difficult if not impossible.

Orthopedic disabilities include "bad" backs, paralysis, and amputation. Divers with orthopedic disabilities may have partial* or total paraplegia (loss of function and, occasionally, of sensation in the lower body) or partial or total quadriplegia (loss of function and sensation from the neck or chest down), or they may have lost all or part of one or both legs and/or arms. Paraplegia, quadriplegia, and amputation can occur as a result of spinal cord injuries, polio, spina bifida, or accidents. People with orthopedic disabilities use wheelchairs, braces and crutches, prosthetic limbs, and a variety of other devices to achieve mobility.

EQUIPMENT

It is essential that divers with disabilities use diving equipment that accommodates their disability and enhances dive safety. Divers with disabilities have found the equipment listed below useful in the following situations:

- Masks—a face mask that has a low volume and a purge permits divers who have limited manual dexterity or reduced lung capacity to clear their mask easily;
- Snorkels—a snorkel that has a purge also permits easy clearing by divers who have limited manual dexterity or reduced lung capacity, and use of a snorkel that has a flexible hose makes snorkel-to-regulator exchange easier. Divers who have upper-extremity prostheses, however, may find it easier to use a fixed J-valve;
- Fins—even divers who have little or no control over their legs find small fins an aid to stability. Fins can also be modified to fit over an amputee's stump or to attach to the hand or wrist to improve the stroking efficiency of arm-stroking divers;
- Wet suits—divers who have paralyzed limbs or who cannot flex their limbs find wet suits (preferably custom made) that have maximum flexibility or zippers over gussets running the length of the suit's arms and legs the easiest to don and doff (Figure A-1). Mitts and boots that have Velcro® or zipper closures are also available;
- Buoyancy compensators—the ideal buoyancy compensator for divers with disabilities is a snug-fitting jacket that has a full front, shoulder inflation, and a "soft-touch" low-pressure inflator (Figure A-2). Velcro® closure of the jacket facilitates donning and doffing, and a pull dump mechanism operated by an oversize knob, handle, or ring makes grasping easier. It is important that all controls be mounted on the diver's functional or stronger side;
- Regulators—divers with disabilities find a low-resistance regulator that has a lightweight second stage most comfortable. The second stage must be mounted on the diver's functional or stronger side. It is important that divers who have upper-limb prostheses or whose manual dexterity is limited carry an octopus or other alternative air supply;

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* The medical community uses the terms "paraparesis" and "quadriparesis," while the disability community uses "partial paraplegia" or "partial quadriplegia."

Figure A-1
Wet Suit with Zippers
Over Gussets

Courtesy Curt Barlow

Figure A-2
Jacket-Type Buoyancy
Compensator

Courtesy Curt Barlow

- Tanks—divers with disabilities prefer to use tanks that are small and cause relatively little drag in the water: 50 cubic-foot (1416 liter) aluminum tanks or 63 cubic-foot (1784 liter) tanks are generally easier to manage than steel tanks, although steel tanks may provide more desirable buoyancy characteristics;
- Weights—traditional weight belts made of nylon webbing that are used with lead "bullets" or blocks provide divers with disabilities with maximum flexibility in terms of weight placement. It is important that the buckle be easy to manipulate and that the belt be comfortable and secure;
- Gauges—to ensure that divers with disabilities can view the necessary gauges (pressure, compass, watch, etc.) at all times, it is possible to design a holder (Figure A-3) for the console that is attached to cross bars and is then secured to the buoyancy compensator with Velcro® strips. Mounting a compass with a side-view window on the console permits the diver to take readings on the surface (Figure A-4). To avoid magnetic interference with the functioning of the compass caused by a metal prosthesis, the compass can be mounted on a nonmetallic rod or be positioned at the head of the console;
- Lights—dive lights must be attached in a manner that permits an arm-stroking diver to have free use of his or her hands. In this situation, the light can be mounted on the mask, wet suit hood, diving helmet, or bicycle helmet with Velcro® fasteners (Figure A-5). A lanyard or holster can be used to attach a light to the waist strap of the buoyancy compensator or to the inflator hose or weight belt. For divers with an upper-extremity prosthesis, a light in a holster can be strapped to the arm; and
- Other equipment—divers with disabilities often carry a compact camera on a strap around their neck or in a zipper bag carried on the weight belt and tank harness. In addition, lift bags that have manual dumps are easier for divers with disabilities to use than those without.

Figure A-3
Holder for Console

Courtesy Curt Barlow

Figure A-4
Side-View Compass
Mounted on Console

Courtesy Curt Barlow

The use of equipment of the types described above enables divers with orthopedic disabilities to perform diving tasks safely and effectively. To ensure that the equipment is easy and efficient to operate, divers should practice using a variety of equipment in a supervised pool environment before using it in the open water. Practice is especially important with buoyancy compensators because it is essential that these devices support the diver at the surface in an upright position.

Adapting Prostheses for Diving Use

Some single- and double-leg amputee divers find that they can get a powerful kick by attaching fins to waterproof prosthetics. Figure A-6 shows a diver putting fins over prosthetic feet that are attached to a leg prosthesis by means of a long bar that can be slipped into the prosthetic leg. The technology for adapting prostheses is not standard, and divers must work with their own prosthetists to develop an appropriate modification. Double amputees need prosthetic sockets that will equalize the length of their legs to facilitate walking on the boat or beach. Rubber pads glued to the bottom of the prosthesis make a non-slip surface, and removable feet can be aligned parallel to the body and be attached to the socket with a long metal rod on top and a Velcro®-closure strap on the foot that loops through a ring on the back of the socket.

A single above-the-knee amputee might use a wooden or otherwise waterproof 'peg leg' attached to a prosthetic socket. A fin could be attached directly to the leg by means of Velcro® and other fasteners. A single below-the-knee amputee might simply mount a fin directly on the socket, since the difference in leg lengths is not great enough to prevent a straight swim. A better (and far more expensive) alternative is to use waterproof prostheses that have drop-ankles that are held in

Figure A-5
Helmet-Mounted
Dive Light

Courtesy Curt Barlow

Figure A-6
Fins Being Placed
on Prosthetic Feet

Courtesy Curt Barlow

a walking position on the boat or beach. After entering the water, the diver pulls a pin that releases the ankles, and the foot flattens out to a swimming position.

Buoyancy must be considered when crafting prostheses for diving. If the buoyancy of the prostheses is either too negative or too positive, the power the prostheses were designed to provide for propulsion will instead be used just to maintain the diver's orientation in the water.

TRAINING FOR DIVERS WITH DISABILITIES

In general, the training of divers with disabilities parallels that for able-bodied divers. An exception to this rule occurs during the first pool or confined-water training session, when it is important that the instructor-to-student ratio be one-to-one. Limiting the size of this first class to a single student allows the instructor to assess the type and extent of the student's disability and to determine what equipment and procedural modifications may be necessary. Once the student is comfortable and confident in the water, and the instructor is assured that the student has the potential to manipulate all of the necessary pieces of equipment and to perform all emergency procedures safely, the student is ready to join group training sessions and to learn those basic water skills that are essential to the safety of all divers.

Basic Water Skills

Before divers enter the water, they must develop a combination of basic water skills, a high level of comfort in the water, and sufficient fitness to enable them to face unexpected stresses calmly and with confidence and competence. The overwhelming majority of individuals who have orthopedic disabilities can develop these skills and this level of physical fitness.

Although there is no consensus about what degree of strength is needed for safe diving or how it can be measured objectively, today's diving certification standards emphasize the diver's basic water skills, fitness, and comfort in the water. These skills and levels of fitness were historically measured by means of timed distance surface swims and distance underwater breathhold swims; however, these methods were developed before it was common for people with disabilities to dive.

Today, diving instructors would agree that all dive training candidates must be able to maintain themselves comfortably on the surface of the water for reasonable periods of time, both in a stationary position and while moving through the water for a specified distance. These requirements emphasize stamina rather than speed, skill, or physical force.

DIVING PROCEDURES

This section describes the steps involved in carrying out a dive and emphasizes the techniques and procedures divers with disabilities have developed to enable them to dive. No diver should dive alone; this basic rule of diving is even more critical for divers with disabilities, who may encounter situations where help is needed to continue the dive.

Communication

During dive planning, it is essential that all divers with disabilities discuss methods of communication that can appropriately be used with the diver's disability. Divers with limited manual dexterity find it difficult to form most conventional hand signals used in diving. They must therefore develop equivalent signals and teach them to their buddies during dive planning.

Early in basic training, it is often a good idea for divers who are forced to rely on buoyancy and weighting for stability and orientation in the water to agree with their instructors on a signal that means, 'I'm not in trouble, but I could use some help.' In addition, because divers with disabilities often tap, squeeze, or poke their buddies to get their attention, divers must know what parts of the body have sensation so that they will know where to touch their buddies when they need help.

Equipment Preparation

The first task in diving is getting diving equipment to the boat or beach. Not all dive sites are easily accessible to individuals with a variety of mobility impairments (wheelchairs, crutches, prostheses, or limited walking endurance). In such cases, assistance may be needed to transport equipment and divers to the site. When the paths between the stored equipment and the dive site are easily negotiable, wheelchair users may be able to carry their tanks on the foot plate of their chair and their equipment bag on their lap (Figure A-7). Others may need to make several trips, carrying a reasonable load each time. In all cases, however, it remains the diver's responsibility to inventory his or her equipment and to ensure that all of it gets to the site.

Equipment Donning

Divers who, for whatever reason, cannot stand while supporting the weight of their diving gear don their tank and jacket-type buoyancy control device (BCD) while sitting down at the water entry point (Figure A-8). To save time in the staging area, all of the gear that can be managed while mobile, including wet suit, mask, and weight belt (assuming the BCD does not have a crotch strap), is donned before moving to the staging area. Once the diver is at the entry point, someone passes the tank over and, if necessary, stabilizes it as the diver puts it on.

When the staging area is a beach without surf, it is easier to enter the water before donning the tank. The tank and BCD are moved out into water deep enough to make them float but not deep enough to present a negative buoyancy problem for the weight belt; this equipment is then donned there.

One of the most trying chores for any diver is getting into a wet suit. A custom-made suit is preferred, but any wet suit with maximum flexibility or with zippers over gussets that extend the length of the suit's arms and legs can be used. Wearing a lycra body suit or nylon stockings as a liner or using a dilute soap solution as a lubricant greatly facilitates the donning of a wet suit.

Figure A-7
Transporting Gear
in the Lap and on
Footplates

Courtesy Curt Barlow

Entries

Drop Entries. Entries involving a drop (from a boat, pier, or dock, for example) are the easiest, cleanest entries for divers who gear up sitting down. There are no standards for graceful seated entries as there are (at least informally) for giant strides and other standing entries. In the case of seated entries, any entry that lands the diver and gear safely in the water is a good entry.

Both forward and back roll entries are used by divers who have limited lower body function. From the seated position, the diver performs whatever version of a roll-over is deemed most comfortable under the circumstances.

The forward roll, used for short drops (less than 2 feet (0.7 m)), is accomplished by leaning forward with the chin tucked to the chest, which permits the diver to

Figure A-8
Donning Gear
While Sitting

Courtesy Curt Barlow

fall straight into the water, landing face first. Some divers prefer to add a sideways twist or to start out sitting slightly sideways so that a shoulder hits the water first.

When dropping into the water from a height of more than 2 feet (0.7 m), such as from a boat with no platform and a high gunwale, it is more comfortable to have the water broken by the tank than the body. Sitting backward on the edge of the gunwale with the tank hanging out over the water, the diver simply falls over backward. For those with lower body paralysis, care should be taken to ensure that the legs are guided over the side. As with any entry, the mask and regulator are held in place by one hand, while the console and any other loose items are held with the other.

Beach Entries. At beaches without surf, there is no need for a fully geared entry, because the tank and BCD are donned in water deep enough to cause them to float. Divers using this technique should remember that their weight belts become negatively buoyant in the water and that they should don their BCD's quickly.

In a seated entry under surf conditions, mobility-impaired divers must don their equipment near the water's edge and move backward into the waves while breathing with their regulator. When the water is deep enough to swim, the diver rolls over and continues beyond the surf zone, remaining either at the surface or submerged.

With either of these beach entries, regulators are likely to pick up an inordinate amount of particulate matter. They should be checked carefully before beginning a descent and will need to be taken in frequently for periodic maintenance.

Snorkel and Regulator Use

Divers with limited manual dexterity, a limited range of motion, or a prosthesis need to practice finding, retrieving, and replacing a snorkel and regulator. A snorkel that has the mouthpiece mounted on a flexible hose is relatively easy to reposition in the mouth; some divers prefer a fixed J-tube. The diver should experiment with different methods of regulator retrieval to find the one that is most effective and should then practice it often. Divers with mildly reduced respiratory strength benefit from selecting easy-breathing regulators and large-volume, smooth-bore, self-draining snorkels that are designed to minimize breathing resistance. In addition, divers should take care not to adjust their weight belts and BCD straps so tightly that their breathing is impaired. A lanyard attaching the mouthpiece to the buoyancy compensator may be useful when the diver has an alternative breathing source. All equipment (regulator, snorkel, BC inflator hose, etc.) must be mounted on the diver's functional or stronger side, in cases where this is an issue.

Ear Clearing

A diver who does not have finger control or who has a prosthesis can accomplish a Valsalva maneuver by various methods. If the diver cannot clear by swallowing or wiggling his or her jaw, the back of the hand can be pressed against the bottom of the mask, or a finger or knuckle of each hand can be used to pinch the nostrils closed.

Mask Clearing

Divers whose lung capacity is reduced generally find the use of a low-volume mask more efficient. Divers who have a limited range of motion in the neck that prevents them from tilting the head upward might consider using a mask with a purge valve.

Buoyancy Control and Descents/Ascents

Because stability on the surface and descents and ascents are accomplished by means of buoyancy control, such control is one of the first skills that must be mastered by divers who do not kick. Divers who use their arms to propel and position themselves in the water cannot afford to use their hands to inflate their BCD's. A power inflation system is thus an absolute requirement for these divers. The system should be capable of quick and easy operation; the best technology now commercially available is the soft-touch power inflator mechanism commonly found on modern BCD's. Divers with limited manual dexterity generally operate the inflate button by pressing it with the right palm against the left palm. There is a need for a technological advance that would allow one-handed operation of the inflation device by individuals who have limited manual dexterity.

Deflation systems should also be quick and easy to operate. For divers with limited manual dexterity or limited sensation, dump cords with a plastic knob on the end or hoses that dump when stretched are often easier to operate than deflate buttons on the end of the inflation/deflation device. Better technology is needed in deflation systems as well.

Divers who use buoyancy control to effect a descent weight themselves heavily enough so that releasing air from the BCD will begin their descent; however, divers must be careful not to overweight themselves. Divers also must remain alert to their increasing negative buoyancy and must constantly compensate by adding the amount of air to the BCD that will slow the descent enough to permit ear clearing and keeping pace with a buddy.

Divers who use buoyancy to control their descent must master a greater number of skills than divers who use kicks to slow their descent. These divers benefit even more than other divers from practicing descents with a descent line before doing ascents to the surface in open water. The descent line can be held in the inside bend of the elbow so that when the arm is bent tight, the descent is stopped and both hands are available to perform other tasks.

Achieving buoyancy control by means of the lungs is a very useful skill for divers and may be especially helpful for students or inexperienced divers who are still becoming accustomed to their inflation/deflation systems. Exhaling and breathing shallowly at the beginning of a descent helps to get the descent under way. Inhaling and keeping the lungs full while taking small breaths adds lift faster than fumbling for, finding, and operating the inflation device. The importance of keeping the airway open while using this technique should be understood before the technique is put to use.

When first learning and practicing buoyancy control, students and inexperienced divers must make a point of remembering that shifting from a horizontal to vertical or vertical to horizontal position under water changes their buoyancy. They should be prepared even as they shift position to make alterations, either via lung control or by manipulating the inflation/deflation device, to maintain neutral buoyancy. Early in the learning experience, divers must also be conscious of the rather sudden compression or decompression of their wet suits and the dramatic effect this can have on buoyancy. With experience, divers make these adjustments automatically, without noticing that they have done so.

Ascents are begun by adding just enough air to the BCD to get the ascent under way. Once initiated, the speed of the ascent is maintained at 60 feet per minute (18.3 m/min) by releasing air from the BCD as the air in the BCD expands and the wet suit decompresses. Practicing ascents along an ascent line should precede making an ascent to the surface in open water. Because it is even more work to maintain a surface position with arms than it is with legs, it is important that divers who do not kick be taught before their first water session to inflate their BCD's before entering the water.

Trim

Maintaining proper trim (balance and position in the water) is essential to the swimming efficiency and control of any diver, whether able-bodied or not. Divers who do not use their legs either to keep their heads constant in relation to their feet or their bodies from rolling from side to side use the careful placement of weight to achieve an efficient position and balance.

On the surface, divers wearing a wet suit may find that their legs float to the surface and push them over onto their backs, a position that some divers find uncomfortable because water splashes into their faces and makes it difficult to see. This situation can be avoided by using a buoyancy compensator that has enough lift to keep the head above the water, combined with the use of leg weights, placed either above the knee or at the ankle. Alternatively, divers needing additional buoyancy in the lower limb region can use negatively buoyant neoprene fins. The amount of weight needed will vary, depending on the individual and the depth of the dive. At deeper depths, divers need less leg weighting because of wet suit compression.

The tendency of a steel tank to pull divers onto their backs can be avoided by adjusting the tank and buoyancy compensator straps so that the tank is held securely in place at the center of the back and by placing the weights at strategic points around the body and holding them in place with Velcro® fasteners. Because it is difficult to fasten the weight belt securely while sitting down, divers must check and tighten the belt as soon as they stretch out prone in the water.

WARNING

Only Jacket-Type BCD's That Hold the Diver Vertical on the Surface Should Be Used by a Diver Who Relies on Buoyancy to Maintain a Comfortable and Safe Surface Posture

Maintaining a horizontal attitude (position) in the water provides the greatest swimming efficiency. Attitude can be controlled partially by the position of the tank; placing the tank closer to the head lowers the head and upper body, and the inherent buoyancy of flaccid lower extremities may further accentuate this problem. If the placement of the tank in the buoyancy compensator does not adequately control the orientation of the diver, weight placement can be adjusted to compensate.

Flaccid legs also tend to drop at the hips, leaving the diver with knees dragging, which is an inefficient swimming position. The most efficient position keeps the shoulders, hips, knees, and feet on the same horizontal plane. Keeping the shoulders, hips, and knees in the same plane and allowing the feet to be in a higher plane is a reasonable compromise and can be achieved by placing weights or extra lift where needed. Wearing wetsuit booties or tennis shoes may raise the feet enough so that the knees are positioned evenly with the shoulders.

Propulsion

Divers who swim with their arms use a variety of strokes for propulsion. The breast stroke is the most common because it is a strong stroke and can be used to maintain head-to-toe orientation in the water and to provide propulsion. Buddies of breast-stroking divers need to swim somewhat above or below the diver to avoid the large sweep of this stroke.

A sculling stroke, in which the arms are held at the sides with the hands sweeping out from the body and then back toward the hips, is a relaxing and graceful stroke. Because it cannot be used to maintain head-to-toe orientation, the diver's trim must be just right for this stroke to work. The sculling stroke is slower than the breast stroke and is appropriate for casual cruising and sightseeing.

When the space needed for strokes with a large sweep is not available, the dog paddle provides effective propulsion. This stroke also can be performed with one hand only, which is useful when the other hand is impaired or occupied with a line, a buddy, or equipment.

Under the right circumstances, pulling along the bottom hand-over-hand can be the strongest method of propulsion. This technique involves the diver grabbing on and pulling himself or herself along a rocky bottom hand-over-hand. On a sandy bottom, the diver can dig a finger or a long tool into the sand to achieve a similar, although weaker, effect. Pulling along the bottom is often the best way to deal with an unexpected current.

Divers with good finger strength can add power to their strokes by wearing webbed gloves. With the fingers spread and cupped, these gloves add up to 10 percent more power to the stroke; they are a good item to keep in the buoyancy compensator's pocket to help out if the current increases.

Buddy Breathing

Although the use of a second stage, or octopus, for buddy breathing is not universal, it is common in diving. Buddy breathing that involves sharing one regulator requires the use of both hands and thus could leave an arm-stroking diver unable to swim or to maintain body position. If propulsion or adjustments in positioning are needed, the buddy-breathing diver must first release the buddy (NOT the regulator); use of this procedure decreases the likelihood that the diver will become separated from his or her air source. Although buddy breathing should be mastered and practiced frequently, it should never be included as a routine part of a dive plan.

NOTE

Divers who swim and maintain their position in the water with their arms should themselves be equipped with an octopus and should dive only with buddies so equipped.

Divers who propel themselves with a wide arm stroke may find octopus buddy breathing easier if they and their buddies mount their octopuses on an extra long hose. Figure A-9 shows an octopus positioned in a readily visible, easily accessible location that makes it

Figure A-9
Octopus Mounted
for Ease of Use

Courtesy Curt Barlow

easy to find, free, and use. Other options include swimming at a slightly sidewise angle or in a one-above-the-other position, moving the stroke above or below the buddy. Again, because divers want to minimize the amount of time their hands are busy, the octopus should be secured in such a way that it is easy to find, uncouple, and pass to a buddy.

Use of Underwater Lines

Arm-stroking divers can use a variety of techniques to follow underwater lines. There is an inverse relationship between the amount of propulsion derived from the stroke and the security of the diver's contact with the line. The most secure method for following a line is to keep the line in the circle formed by the thumb and forefinger when the hand is in the 'OK' position. Using the hand circling the line for propulsion is ineffective, and a one-handed dog paddle is thus the only workable stroke when a line is being held. Opening the hand and keeping the line against the area between the thumb and forefinger provides less security but permits greater use of the hand. The hand can be moved forward and backward along the line in a shortened breast stroke. More propulsion but less security can be achieved by swimming just a bit above the line, which keeps the line in contact with the underside of the arm as the arm moves up and back in a full breast stroke. The circumstances of each dive determine how much security is needed, i.e., an increase in the likelihood of a silt-out indicates the need for greater security.

The easiest way to lay a line while swimming with the arms is to use a line reel with a braking mechanism and a long handle that can be tucked under the weight belt or buoyancy compensating device's waist strap. With the braking mechanism set to keep a constant, moderate tension on the line, the diver tucks the line reel under a belt or strap and swims along until a tie-off is needed. After tying off, the reel is again tucked under the belt or strap until the next tie-off. Careful attention is paid to making sure that the reel does not drop away unnoticed. Attaching the reel with a snap hook makes dropping the line reel virtually impossible.

A self-retracting or otherwise one-handed line reel is not yet available, so reeling in a line is necessarily a two-handed job. Consequently, divers who swim with the arms pull themselves along the line as they reel it in. The extra strain this puts on the line must be considered both when selecting line for the reel and when tying off. Although anyone who dives in circumstances necessitating the use of a line must be proficient at laying and reeling in a line, it usually is wiser for a kicking member of the dive team to work the line; only if that diver becomes incapacitated should the arm-stroking diver tend the line.

Exits

Exiting the water is often difficult for a diver who does not walk up a beach or climb a ladder. At the end of a dive, mobility-impaired divers usually remove their equipment in the water. The weight belt is always removed before the buoyancy compensator and tank to avoid leaving the diver too negatively buoyed.

Onto Boats or Piers. The easiest exits for mobility-impaired divers to negotiate are those onto boats that have a water-level dive platform and a walk-through transom. Divers who can do so hoist themselves onto the platform and then, while seated, pull themselves backward to the deck via the walk-through transom. On a pier or dock that has steps (rather than a ladder) leading out of the water, divers can sit and hoist themselves up one step at a time until they reach the dock.

Onto the Beach. Beach exits in calm conditions can be accomplished by having the diver drag himself or herself backward out of the water while seated. If there is surf, the diver keeps his or her equipment in place, swims as far as possible, and then crawls on his or her elbows until the surf zone is reached; the regulator is kept in the mouth during the exit process.

Assisted Exits. In some cases, it is useful for the mobility-impaired diver to get help from another diver. It is often easiest for one or two buddies to grasp the diver under the armpits (Figure A-10) or by the hands (depending on the height from the water) and to pull the diver up the beach or to the deck or platform level, perhaps with one assistant in the water to help lift or guide the legs. On some boats where the gunwale is so high that a diver in the water cannot be reached by buddies on the boat, a very strong buddy may be able to carry the diver up the ladder. For any person lifting another, care must be taken to ensure proper lifting techniques so that the lifter is not injured. Davits or other lifting devices can also be useful in such situations.

If the boat is a sailboat, a variety of lifting devices can be fashioned. To remove a diver from the water, the boom can be positioned over the diver in the water, a bosun's chair can be attached to the boom, and the diver can hoist himself or herself up by means of a block and tackle. When the diver is at the level of the deck, the boom is swung across to the cockpit, and the diver then lowers himself or herself to the seat. To lift a diver to a level higher than the deck, such as onto a pier, the bosun's chair can be attached to the main halyard, and the diver can then be lifted by means of a winch.

The difficulty in removing a mobility-impaired diver from the water is also a measure of how difficult it would be to remove an unconscious or otherwise incapacitated victim. By creating systems that make it easier for mobility-impaired divers, a boat is made safer for any diver who may, for emergency reasons, need to be lifted from the water.

OTHER CONSIDERATIONS

Thermoregulation

Some disabilities are associated with an increased sensitivity to extremes of temperature. Chilling can occur much faster in individuals with decreased circulation; in addition, individuals with paralyzed extremities may not develop or perceive the early symptoms of hypothermia. Overheating can be a significant problem for people who, like some people with spinal cord injuries, do not sweat. Carrying a pocket-sized reflective emergency blanket is a good precaution for dealing with an unexpectedly cold post-dive boat ride. Pouring water over the skin acts like artificial sweat and effectively cools the body. Finally, warm water can be poured into the diver's suit after he or she exits the dive, which will greatly aid in restoring warmth. Because the effects of hypothermia or hyperthermia can be serious, divers should plan ahead to stay as warm as possible in cool conditions (especially under water) and as cool as possible in warm conditions.

Figure A-10
Diver Being
Assisted from
the Water

Courtesy Curt Barlow

Catheters

Various types of catheters are worn by many individuals with disabilities. If an external catheter and a leg bag are worn, the bag should be emptied before the dive (and should perhaps be left open during the dive), since immersion in the water tends to cause people to urinate. A plug can be made for an indwelling catheter using a cut-up leg bag (use only the top piece that has the one-way valve). Such a plug enables urine to drain during the dive and prevents salt water and impurities from entering the catheter.

Protection of Paralyzed Tissue

Blankets or cushions should be used to prevent bruising or the development of pressure sores. In cooler water, the wet suit will protect the skin; in warm water, clothing such as a lycra body suit will protect against coral scrapes and jellyfish stings.

Decompression Sickness

Divers with orthopedic disabilities are concerned about the extent of their susceptibility to decompression sickness. It has been speculated that unused tissues, such as those in paralyzed limbs, may off-gas at a different rate than is the case for active tissues. To date, there have been no scientific studies exploring this issue. It is known, however, that paralyzed limbs have some degree of reduced circulation and that circulation is important to the safe uptake and elimination of nitrogen. Any diver with reduced circulation (including smokers, for example) needs to use the U.S. Navy dive tables conservatively. Divers who have disabilities that may affect the rate of off-gassing should add safety factors when they use the tables. Some divers add 10 minutes to their bottom time and/or 10 feet (3 m) to their depth. Others stay well under the no-decompression limit on their first dive and then penalize themselves one or two repetitive group designations when they plan their subsequent dives. Finally, many divers routinely do a stop between 10 and 20 fsw (3-6 m) for a few minutes even when the dive was well within the no-decompression limits.

Autonomic Dysreflexia

Divers who are susceptible to autonomic dysreflexia are aware that conditions commonly encountered in diving may trigger this condition. Just as hypothermia or hyperthermia can be prevented by taking necessary precautions, autonomic dysreflexia can be avoided by divers who are aware that extra care is needed. Autonomic dysreflexia can cause a medical emergency for people with spinal cord injuries at or above the T-5 level, and in some cases for people whose injury is between T-6 and T-10. This condition can occur when there is an irritating stimulus, such as a full bladder, a pressure sore, or an ingrown toenail, below the level of the injury. The stimulus sends nerve impulses to the spinal cord, where they travel upward until they become blocked at the level of the injury. The impulses never reach the brain, but they do trigger increased sympathetic autonomic nervous system activity. The resulting spasms and narrowing of the blood vessels cause the blood pressure to rise and, eventually, the heartbeat to slow. Autonomic dysreflexia can lead to seizures, unconsciousness, stroke, or, if untreated, death.

The signs and symptoms of autonomic dysreflexia include a pounding headache, slow pulse, sweating above the level of the injury, goose bumps, blotching of the skin, and nasal congestion. The condition can be caused by anything that would have been painful or physically stimulating before the injury, but it is most often caused by a full bladder. Emergency treatment of the condition involves getting the victim into (or maintaining him or her in) a sitting position to help decrease the blood pressure, loosening anything that may be pressing on the abdominal area, and finding and correcting the cause (often a plugged catheter, a full drainage bag, or the need for an intermittent catheterization).

To avoid having a problem with autonomic dysreflexia, divers with disabilities that can be associated with this condition need to be told in detail about certain aspects of the planned dive; for example, prolonged immersion in cold water, which increases the rate of bladder filling, or the absence of wheelchair-accessible toilet facilities could both contribute to the development of autonomic dysreflexia.

SUMMARY

The procedures, equipment, and specialized techniques described above show that trained and experienced divers with disabilities can dive safely and efficiently. In addition, this section demonstrates the importance of intensive training, thorough predive planning, effective communication, and use of the buddy system for divers with disabilities.

APPENDIX B
U.S.NAVY AIR DECOMPRESSION TABLES

APPENDIX B
U.S. NAVY AIR DECOMPRESSION TABLES

INTRODUCTION

When air is breathed under pressure, inert nitrogen diffuses into various tissues of the body. This nitrogen uptake by the body continues, at different rates for the various tissues, as long as the partial pressure of the inspired nitrogen is higher than the partial pressure of the gas absorbed in the tissues. Consequently, the amount of nitrogen absorbed increases with the partial pressure of the inspired nitrogen (depth) and the duration of the exposure (time).*

When the diver begins to ascend, this process is reversed: the nitrogen partial pressure in the tissues exceeds that in the circulatory and respiratory systems. The pressure gradient from the tissues to the blood and lungs must be carefully controlled to prevent nitrogen from coming out of solution in the form of bubbles. If the pressure gradient is uncontrolled, bubbles of nitrogen gas can form in tissues and blood and cause decompression sickness.

To prevent decompression sickness, several decompression tables have been established. These tables take into consideration the amount of nitrogen absorbed by a diver's body at various depths for given time periods. They also consider both the allowable pressure gradients that can exist without excessive bubble-formation and the different gas elimination rates associated with various body tissues. Stage decompression, which requires that the diver make stops of specific durations at given depths during ascent, is used in air diving because of its operational simplicity.

The U.S. Navy decompression tables are the result of years of scientific study, mathematical modeling, human and animal studies, and extensive field experience. These tables thus contain the best overall information available; however, as dive depth and time increase, these tables become less accurate and thus require careful application. To ensure maximum diver safety, these tables also must be followed strictly. Deviations from established decompression procedures should be made only under emergency conditions and with the consent of the NOAA Diving Coordinator.

Five different tables are discussed in this chapter, and each has a unique application in air diving. Four of these tables provide specific decompression data for use under various operational conditions; the remaining table is used to determine decompression requirements in situations where a diver has conducted or will be conducting more than one dive in a 12-hour period. Before using any of these tables, divers should read Sections 14.6 through 14.9 of this manual.

DEFINITION OF TERMS

Terms which are frequently used when discussing decompression tables are defined below.

Bottom Time - The total amount of time that elapses from the time a diver leaves the surface in descent to the time (next whole minute) he or she begins ascent; bottom time is measured in minutes.

Decompression Stops - Stops that a diver must make for specified times and at specified depths during ascent from a decompression dive. The depths at which decompression stops must take place and the time that the diver must remain at each stop are specified in the decompression schedule being followed.

Decompression Schedule - A list of depths and times that indicates the decompression stops that a diver must make for dives having particular maximum depths and bottom times; decompression schedules are indicated as feet/minutes.

Decompression Table - A set of decompression schedules, or limits, usually organized in order of increasing bottom times and depths.

Depth - When used in connection with the depth of a dive, the following terms are used:

1. **Deepest Depth:** The depth indicated by the deepest pneumofathometer reading during a surface-supplied dive or the depth shown by the deepest depth gauge reading during a scuba dive.
2. **Maximum (Max) Depth:** In surface-supplied operations, the deepest depth plus 5 feet (1.5 m); the max depth is used to select a decompression schedule. In scuba operations, the max depth and the deepest depth are the same.
3. **Stage Depth:** The depth indicated by a pneumofathometer reading taken when the diver is on the stage and ready to leave the bottom. The stage depth is used to compute distance and travel time to the first stop.

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* The material in this appendix has been adapted from the US Navy Diving Manual (1988).

Equivalent Single Dive Bottom Time - The time in minutes used to select a schedule for a single repetitive dive; the equivalent single dive bottom time is equal to the bottom time of the planned repetitive dive and the diver's residual nitrogen time.

No-Decompression Time - The maximum amount of time that a diver can spend at a given depth and still be able to make a safe ascent directly to the surface at a prescribed rate and without taking any decompression stops.

Repetitive Dive - Any dive conducted within a 12-hour period after a previous dive.

Repetitive Group Designation - A letter that designates the amount of nitrogen remaining in a diver's body during the 12-hour period following a dive.

Residual Nitrogen - The amount of nitrogen gas that remains in a diver's tissues after the completion of a dive.

Residual Nitrogen Time - The time, in minutes, that must be added to the bottom time of a repetitive dive to compensate for the nitrogen remaining in the diver's tissues from a previous dive.

Single Dive - Any dive conducted more than 12 hours after a previous dive.

Single Repetitive Dive - Any dive performed by a diver whose tissues still contain residual nitrogen from a previous dive; to select an appropriate decompression schedule for a repetitive dive, the actual bottom time of the planned dive must be added to the diver's residual nitrogen time.

Surface Interval - The period of time that a diver spends on the surface after a dive; the interval begins as soon as the diver surfaces and ends as soon as the diver starts his or her next descent.

TABLE SELECTION

The following U.S. Navy air decompression tables are available:

- Standard Air Decompression Table
- No-Decompression Limits and Repetitive Group Designation Table
- Surface Decompression Table Using Oxygen
- Surface Decompression Table Using Air

These tables each contain a series of decompression schedules that must be adhered to rigidly during ascent from an air dive. Conditions surrounding the dive dictate which decompression table and schedule are selected. These conditions are status of the diver, depth and duration of the dive, availability of an oxygen breathing system within the chamber, and environmental conditions such as sea state, water temperature, etc.

The **Surface Decompression Table Using Oxygen** or the **Surface Decompression Table Using Air** may be used to make up a diver's omitted decompression only if the diver's emergency surfacing occurs at a point in the decompression when water stops are not required (or have already been taken) and all of the conditions for use of this table have been met.

The **Residual Nitrogen Timetable for Repetitive Air Dives** (hereafter called the Residual Nitrogen Timetable) is not a decompression table in the strictest sense; its purpose is to provide the information needed to plan repetitive dives.

No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Air Dives

The **No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Air Dives** (hereafter called the No-Decompression Table) serves two purposes. First, it summarizes all the depth and bottom time combinations for which no decompression is required. Second, it provides the repetitive group designation for any no-decompression dive. (Even on no-decompression dives, some nitrogen remains in the diver's tissues after the dive; if a diver dives again within a 12-hour period, he or she must consider this residual nitrogen when calculating decompression requirements.)

Every depth listed in the No-Decompression Table has a corresponding no-decompression limit in minutes. This limit is the maximum bottom time that a diver may spend at that depth without needing decompression. The columns to the right of the no-decompression limits column are used to determine the repetitive group designation that is assigned to the diver after every dive. To find a diver's repetitive group designation, enter the table at the depth equal to or next greater than the maximum depth of the dive and follow that row until you reach the bottom time that is equal to or just greater than the actual bottom time of the dive; then follow that column upward to the repetitive group designation.

In the No-Decompression Table, depths shallower than 35 fsw (10 m) do not have a specific no-decompression limit. Implied time limits do pertain to these depths, however, because repetitive group designations are not provided for bottom times of greater than 6 hours. A 6-hour bottom time is the maximum time permitted by the No-Decompression Table, and diving should not be conducted for times longer than this limit.

Any dive deeper than 35 fsw (10 m) that has a bottom time greater than the no-decompression limit given in the No-Decompression Table is by definition a decompression dive and must be conducted in accordance with the **Standard Air Decompression Table.**

Selection of the Appropriate Decompression Schedule

The decompression schedules for all decompression tables are given in 10- or 20-foot (3 or 6.1 m) depth increments and, usually, in 5- or 10-minute bottom time increments. The depth and bottom time combinations of actual dives, however, rarely match any decompression schedule exactly. To ensure that the decompression schedule selected is conservative (i.e., on the safe side): **(1) always select a schedule that has a depth that is equal to or next greater than the maximum depth of the actual dive, and (2) always select a schedule that has a bottom time that is equal to or next longer than the bottom time of the actual dive.**

If the Standard Air Decompression Table, for example, is being used to select a schedule for a dive to 97 fsw (29 m) for 31 minutes, the following procedure is used. First, add 5 fsw (1.5 m) to the depth of the dive (i.e., 97 fsw + 5 fsw = 102 fsw). Then, select the schedule for a 102-fsw dive; this would be the 110-fsw schedule. Finally, select the appropriate schedule for a 31-minute dive; this would be the 40-minute schedule. Thus, the dive would be conducted in accordance with the 110/40 schedule.

WARNING

Never Attempt To Interpolate Between Decompression Schedules

If a diver is exceptionally cold during a dive or the work load is strenuous, the decompression schedule for the **next longer duration** should be selected. For example, the normal schedule for a dive to 90 fsw (27 m) for 34 minutes would be the 90/40 schedule. However, if the divers are cold or fatigued, they should decompress according to the 90/50 schedule.

AIR DECOMPRESSION TABLES

U.S. Navy Standard Air Decompression Table

The **Standard Air Decompression Table** combines two former tables—the Standard Air Table and the Exceptional Exposure Air Table—into a single table. To distinguish clearly between standard and exceptional exposure decompression schedules, exceptional exposure schedules on this table are printed in **Blue**.

As shown on this table, no decompression is required if the bottom time of the dive is less than the first bottom time listed for the dive's depth; in such cases, the divers may ascend directly to the surface at a rate of 60 feet per minute (fpm) (18.3 m/min). The repetitive group designations for no-decompression dives are shown in the No-Decompression Table.

As noted in the Standard Air Decompression Table, there are no repetitive group designations for exceptional exposure dives. **Repetitive dives are not permitted after an exceptional exposure dive.**

Example: A diver has just completed a dive to a depth of 143 fsw (43 m) for 37 minutes. The diver is not unusually cold or fatigued. What is the diver's decompression schedule and repetitive group designation?

Solution: To determine the appropriate decompression schedule and the diver's repetitive group designation at the end of the decompression, select the depth equal to or next deeper than the depth of the dive and the bottom time equal to or next longer than the bottom time of the dive. In the example, this would be the 150/40 schedule.

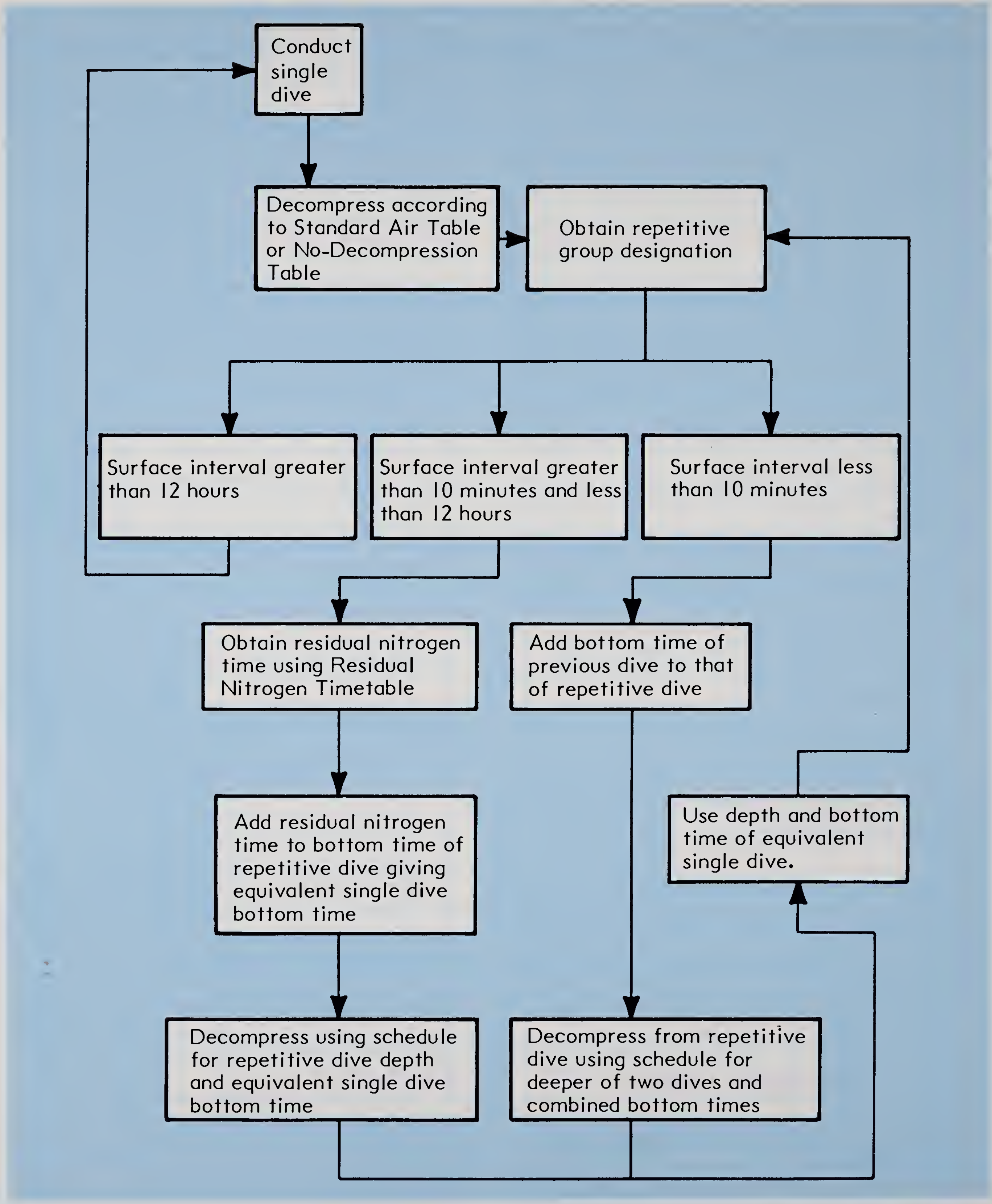
Repetitive Dives

During the 12-hour period after an air dive, the quantity of residual nitrogen in a diver's body gradually returns to its normal level. If divers are to make a second dive (repetitive dive) within this 12-hour interval, they must consider the amount of residual nitrogen in their tissues when planning for the dive.

The procedures for conducting a repetitive dive are summarized in Figure B-1. When divers complete their first dive, the Standard Air Decompression Table or the No-Decompression Table assigns them a repetitive group designation. The repetitive group designation assigned to a diver immediately after surfacing applies only to the amount of nitrogen remaining in his or her tissues at that time. As nitrogen leaves the tissues and blood over time, a diver's repetitive group designation changes. The Residual Nitrogen Timetable permits the appropriate residual nitrogen designation to be determined at any time during the diver's surface interval.

Just before a diver begins a repetitive dive, his or her residual nitrogen time should be determined using the Residual Nitrogen Timetable. The residual nitrogen time is then added to the actual bottom time of the planned repetitive dive, and the new bottom time, called the equivalent single dive time, is used to select the

Figure B-1
Repetitive Dive Flowchart



Source: U.S. Navy (1988)

appropriate schedule to use for decompression after the repetitive dive. Equivalent single dives that require the use of exceptional exposure decompression schedules should not be conducted. To assist in selecting the decompression schedule for a repetitive dive, a systematic repetitive dive worksheet, shown in Figure B-2, should always be used.

If a diver wishes to make a third dive after his or her first repetitive dive, the depth and bottom time of the first equivalent single dive should be inserted into part one of the second repetitive dive worksheet.

Residual Nitrogen Timetable for Repetitive Air Dives

The quantity of residual nitrogen in a diver's tissues immediately after a dive is expressed by the repetitive group designation assigned either by the Standard Air Decompression Table or the No-Decompression Table. The upper portion of the Residual Nitrogen Timetable shows a range of times between 10 minutes and 12 hours, expressed in hours:minutes (2:21 = 2 hours 21 minutes). Each interval has two limits: a minimum time (top limit) and a maximum time (bottom limit).

Residual nitrogen times (in minutes) corresponding to the depths of various repetitive dives are shown in the body of the lower portion of the Residual Nitrogen Timetable. To determine the residual nitrogen time for a repetitive dive, locate the diver's repetitive group designation from the previous dive along the diagonal line above the table. Read horizontally until you reach the time interval that includes the diver's surface interval. (The time the diver spends on the surface must be equal to or lie between the time limits of this interval.) Next, read vertically downward to obtain the diver's new repetitive group designation, which reflects the amount of residual nitrogen left in the diver's body at the present time. Continue downward in this same column until you reach the row that includes the depth of the planned repetitive dive. The time, in minutes, shown at the intersection is the residual nitrogen time that must be added to the bottom time of the planned repetitive dive.

If a diver's surface interval is less than 10 minutes, the residual nitrogen time is simply the bottom time of the previous dive. If the planned repetitive dive is to be made to a depth that is equal to or greater than the depth of the diver's previous dive, the residual nitrogen time may turn out to be longer than the bottom time of the previous dive. In this event, the bottom time of the previous dive should be added to the bottom time of the planned repetitive dive to obtain the diver's equivalent single dive time. Because all of the residual nitrogen in a diver's tissues has passed out of the diver's body after 12 hours, a dive conducted more than 12 hours after the diver surfaced from the first dive is not considered a repetitive dive.

Example: A repetitive dive is to be made to 98 fsw (27.3 m) for an estimated bottom time of 15 minutes. The previous dive was to a depth of 102 fsw (30 m) and had a 48-minute bottom time. The diver's surface interval is 6 hours 28 minutes (6:28). What is the correct decompression schedule for the repetitive dive?

Solution: Add the residual nitrogen time of the previous dive to the bottom time of the planned repetitive dive to obtain the diver's equivalent single dive time. The correct decompression schedule for the repetitive dive would then be the 100/25 schedule. Figure B-3 depicts the dive profile for this situation.

Surface Decompression

Surface decompression is a technique for fulfilling all or a portion of a diver's decompression obligation in a recompression chamber. Use of this technique greatly reduces the time that a diver must spend in the water; moreover, breathing oxygen in a recompression chamber reduces the amount of time a diver must spend in decompression.

Surface decompression also significantly enhances a diver's safety: the shorter in-water exposure time made possible by surface decompression keeps divers from chilling to a dangerous level, and the constant-pressure recompression chamber environment means that divers can be protected from surface conditions. In a chamber, the diver can also be observed constantly by the chamber operator and be monitored as necessary by medical personnel; this kind of monitoring allows any sign of decompression sickness to be detected readily and treated immediately.

If the recompression chamber has an oxygen breathing system, surface decompression should be conducted in accordance with the Surface Decompression Table Using Oxygen. If air is the only breathing medium available in the chamber, the Surface Decompression Table Using Air must be used. No surface decompression table is available for decompression from an exceptional exposure dive.

Residual nitrogen times have not been developed for repetitive dives. However, repetitive dives can be made as long as the sum of the bottom times of all the dives made by a diver in the previous 12 hours and the maximum depth ever attained by the diver do not exceed the maximum time/depth combinations shown in the Surface Decompression Table Using Oxygen (170 fsw (51.8 m)/40 min) or the Surface Decompression Table Using Air (190 fsw (57 m)/60 min) limits.

Figure B-2
Repetitive Dive Worksheet

REPETITIVE DIVE WORKSHEET

DATE

I. PREVIOUS DIVE:

_____ minutes ☐ Standard Air Table ☐ No-Decompression Table
____+____=____ feet ☐ Surface Table Using Oxygen ☐ Surface Table Using Air
_____ repetitive group letter designation

2. SURFACE INTERVAL:

_____ hours _____ minutes on surface
_____ repetitive group from item I above
_____ new repetitive group letter designation from Residual Nitrogen Timetable

3. RESIDUAL NITROGEN TIME:

____+____=____ feet, depth of repetitive dive
_____ new repetitive group letter designation from item 2 above
_____ minutes, residual nitrogen time from Residual Nitrogen Timetable or bottom time of previous Sur D dive

4. EQUIVALENT SINGLE DIVE TIME:

_____ minutes, residual nitrogen time from item 3 above or bottom time of previous Sur D dive
\+ _____ minutes, actual bottom time of repetitive dive
= _____ minutes, equivalent single dive time

5. DECOMPRESSION FOR REPETITIVE DIVE:

_____ minutes, equivalent single dive time from item 4 above
____+____=____ feet, depth of repetitive dive

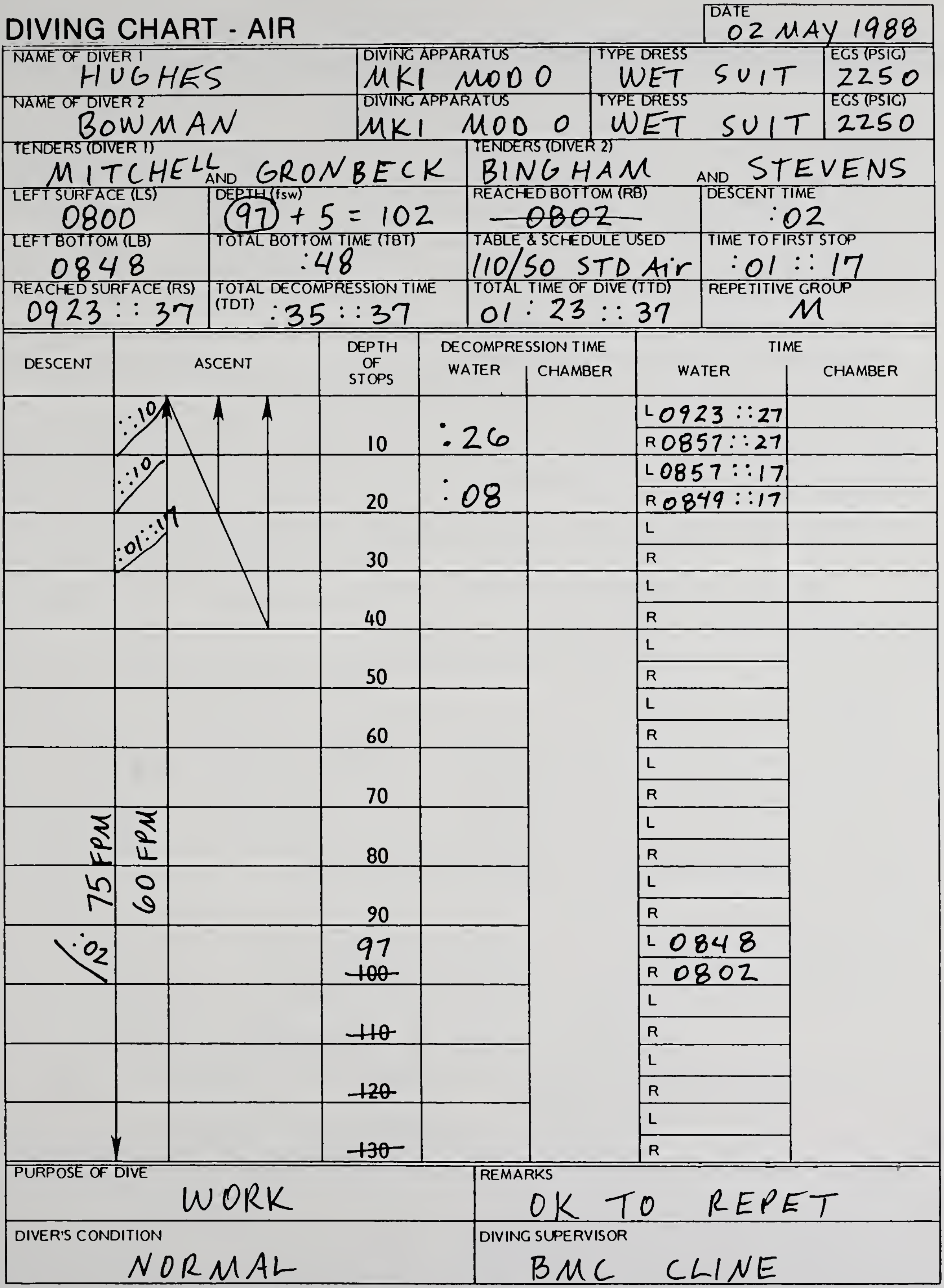
Decompression from (check one):
☐ Standard Air Table ☐ No-Decompression Table
☐ Surface Table Using Oxygen ☐ Surface Table Using Air

	Depth	Water	Chamber
Decompression Stops:	_____ feet	_____ minutes	_____ minutes
	_____ feet	_____ minutes	_____ minutes
	_____ feet	_____ minutes	_____ minutes
	_____ feet	_____ minutes	_____ minutes
	_____ feet	_____ minutes	_____ minutes

__________ schedule used (depth/time)
_____ repetitive group letter designation

Source: U.S. Navy (1988)

Figure B-3A
Repetitive Dive Chart



DIVING CHART - AIR

DATE: 02 MAY 1988

NAME OF DIVER 1: HUGHES
DIVING APPARATUS: MKI MOD 0
TYPE DRESS: WET SUIT
EGS (PSIG): 2250

NAME OF DIVER 2: BOWMAN
DIVING APPARATUS: MKI MOD 0
TYPE DRESS: WET SUIT
EGS (PSIG): 2250

TENDERS (DIVER 1): MITCHELL AND GRONBECK
TENDERS (DIVER 2): BINGHAM AND STEVENS

LEFT SURFACE (LS): 0800
DEPTH (fsw): 97 + 5 = 102
REACHED BOTTOM (RB): ~~0802~~
DESCENT TIME: :02

LEFT BOTTOM (LB): 0848
TOTAL BOTTOM TIME (TBT): :48
TABLE & SCHEDULE USED: 110/50 STD Air
TIME TO FIRST STOP: :01 :: 17

REACHED SURFACE (RS): 0923 :: 37
TOTAL DECOMPRESSION TIME (TDT): :35 :: 37
TOTAL TIME OF DIVE (TTD): 01 : 23 :: 37
REPETITIVE GROUP: M

DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME		TIME	
			WATER	CHAMBER	WATER	CHAMBER
	::10	10	:26		L 0923 ::27 R 0857 ::27	
	::10	20	:08		L 0857 ::17 R 0849 ::17	
	:01::17	30			L R	
		40			L R	
		50			L R	
		60			L R	
		70			L R	
75 FPM	60 FPM	80			L R	
		90			L R	
:02		97 ~~100~~			L 0848 R 0802	
		~~110~~			L R	
		~~120~~			L R	
		~~130~~			L R	

PURPOSE OF DIVE: WORK
REMARKS: OK TO REPET

DIVER'S CONDITION: NORMAL
DIVING SUPERVISOR: BMC CLINE

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

Figure B-3B
(Continued)

REPETITIVE DIVE WORKSHEET

DATE 02 MAY 88

1. PREVIOUS DIVE:

48 minutes ☑ Standard Air Table ☐ No-Decompression Table
97 + 5 = 102 feet ☐ Surface Table Using Oxygen ☐ Surface Table Using Air
M repetitive group letter designation

2. SURFACE INTERVAL:

6 hours 28 minutes on surface
M repetitive group from item 1 above
B new repetitive group letter designation from Residual Nitrogen Timetable

3. RESIDUAL NITROGEN TIME:

93 + 5 = 98 feet, depth of repetitive dive
B new repetitive group letter designation from item 2 above
7 minutes, residual nitrogen time from Residual Nitrogen Timetable or bottom time of previous Sur D dive

4. EQUIVALENT SINGLE DIVE TIME:

7 minutes, residual nitrogen time from item 3 above or bottom time of previous Sur D dive
\+ 15 minutes, actual bottom time of repetitive dive
= 22 minutes, equivalent single dive time

5. DECOMPRESSION FOR REPETITIVE DIVE:

22 minutes, equivalent single dive time from item 4 above
93 + 5 = 98 feet, depth of repetitive dive

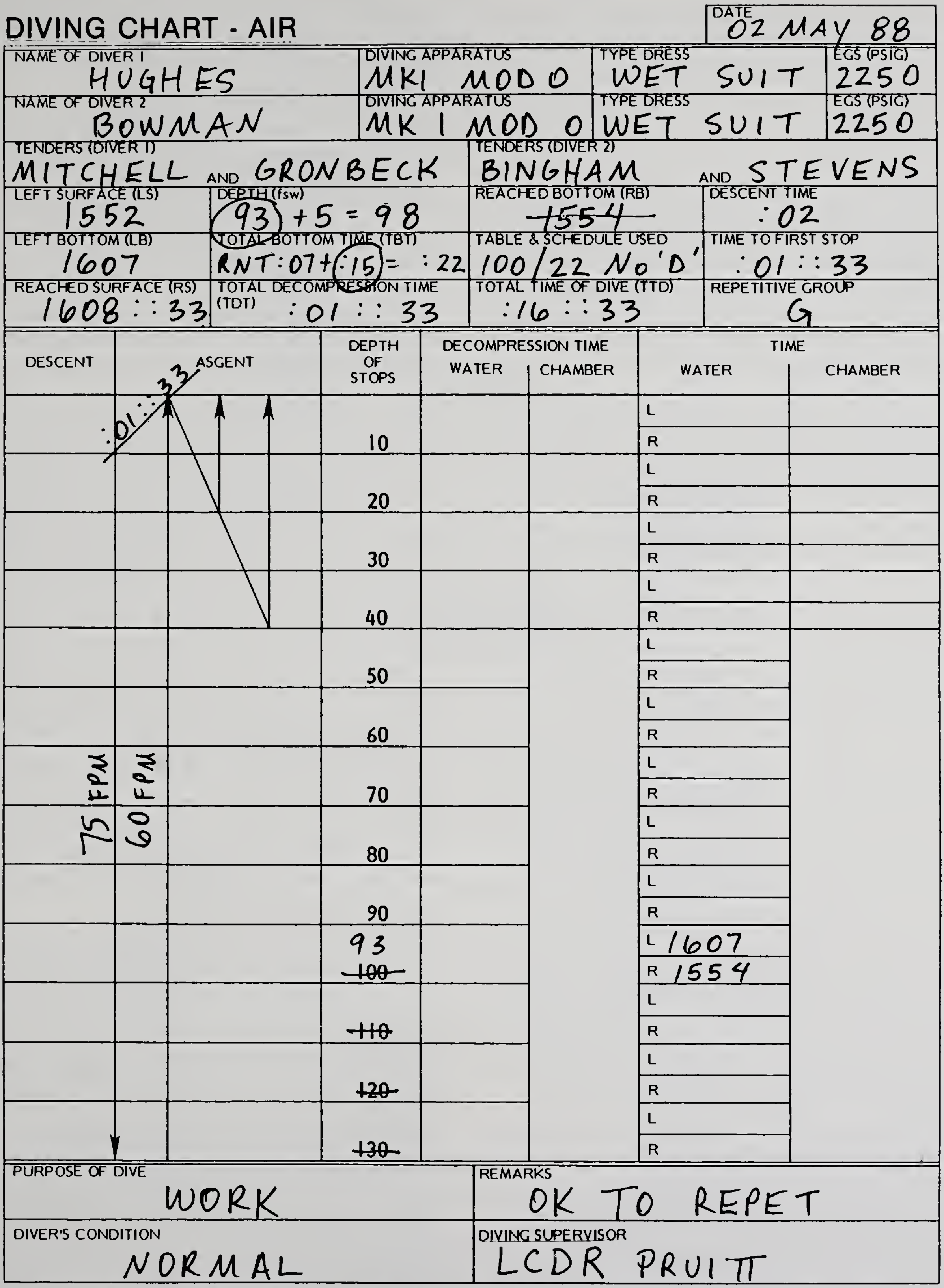
Decompression from (check one):
☐ Standard Air Table ☑ No-Decompression Table
☐ Surface Table Using Oxygen ☐ Surface Table Using Air

	Depth	Water	Chamber
Decompression Stops:	____ feet	____ minutes	____ minutes
	____ feet	____ minutes	____ minutes
	____ feet	____ minutes	____ minutes
	____ feet	____ minutes	____ minutes
	____ feet	____ minutes	____ minutes

100/22 schedule used (depth/time)
G repetitive group letter designation

Source: U.S. Navy (1988)

Figure B-3C
(Continued)



DIVING CHART - AIR

DATE 02 MAY 88

NAME OF DIVER 1 HUGHES	DIVING APPARATUS MK1 MOD 0	TYPE DRESS WET SUIT	EGS (PSIG) 2250
NAME OF DIVER 2 BOWMAN	DIVING APPARATUS MK 1 MOD 0	TYPE DRESS WET SUIT	EGS (PSIG) 2250
TENDERS (DIVER 1) MITCHELL AND GRONBECK		TENDERS (DIVER 2) BINGHAM AND STEVENS	
LEFT SURFACE (LS) 1552	DEPTH (fsw) 93 +5 = 98	REACHED BOTTOM (RB) ~~1554~~	DESCENT TIME :02
LEFT BOTTOM (LB) 1607	TOTAL BOTTOM TIME (TBT) RNT:07+(:15)= :22	TABLE & SCHEDULE USED 100/22 No 'D'	TIME TO FIRST STOP :01::33
REACHED SURFACE (RS) 1608::33	TOTAL DECOMPRESSION TIME (TDT) :01::33	TOTAL TIME OF DIVE (TTD) :16::33	REPETITIVE GROUP G

DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME WATER	DECOMPRESSION TIME CHAMBER	TIME WATER	TIME CHAMBER
		10			L R	
		20			L R	
		30			L R	
		40			L R	
		50			L R	
		60			L R	
		70			L R	
		80			L R	
		90			L R	
		93 ~~100~~			L 1607 R 1554	
		~~110~~			L R	
		~~120~~			L R	
		~~130~~			L R	

PURPOSE OF DIVE WORK	REMARKS OK TO REPET
DIVER'S CONDITION NORMAL	DIVING SUPERVISOR LCDR PRUITT

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

If a diver has exceeded his or her allowable surface interval or displays signs of decompression sickness, the diver should be treated in accordance with the procedures discussed below for surface decompression using air or oxygen.

Surface Decompression Table Using Oxygen

To use the Surface Decompression Table Using Oxygen, an approved recompression chamber with an oxygen breathing system is required. The ascent rate to the first decompression stop, or to the surface if no water stops are required, is 25 fpm (7.5 mpm). The ascent time between each stop, and from the 30-foot (9 m) stop to the surface, is 1 minute.

Once the divers are on the surface, the tenders must remove the diver's breathing apparatus and assist the diver into the recompression chamber, all within a 3.5-minute period. The divers begin to breathe oxygen as soon as they enter the chamber. Pressurization of the chamber with air should take about 30 seconds, which means that the total time that will have elapsed from the time the diver left the 30-foot (9 m) water stop to the time that he or she reaches the 40-foot (12.2 m) recompression chamber stop **has not exceeded 5 minutes**. Five minutes is the maximum amount of time that can elapse without endangering the diver.

If the prescribed surface interval has been exceeded and the divers show no signs of decompression sickness, they are treated as if they had Type I decompression sickness symptoms. If the divers are symptomatic, they must be treated as if they had Type II decompression sickness symptoms. Symptoms occurring during chamber stops are treated as if they were decompression sickness recurrences.

As soon as the divers enter the chamber, they must begin to breathe pure oxygen. The divers must remain on oxygen down to and throughout the designated 40-foot (12.2 m) stop time (except for the 5-minute air break described below). On completion of the designated 40-foot (12.2 m) chamber stop, the chamber should be surfaced at a constant rate of 20 fpm (6.1 mpm) over a 2-minute period.

During chamber stops, the divers are to continue to breathe oxygen, with the following exceptions:

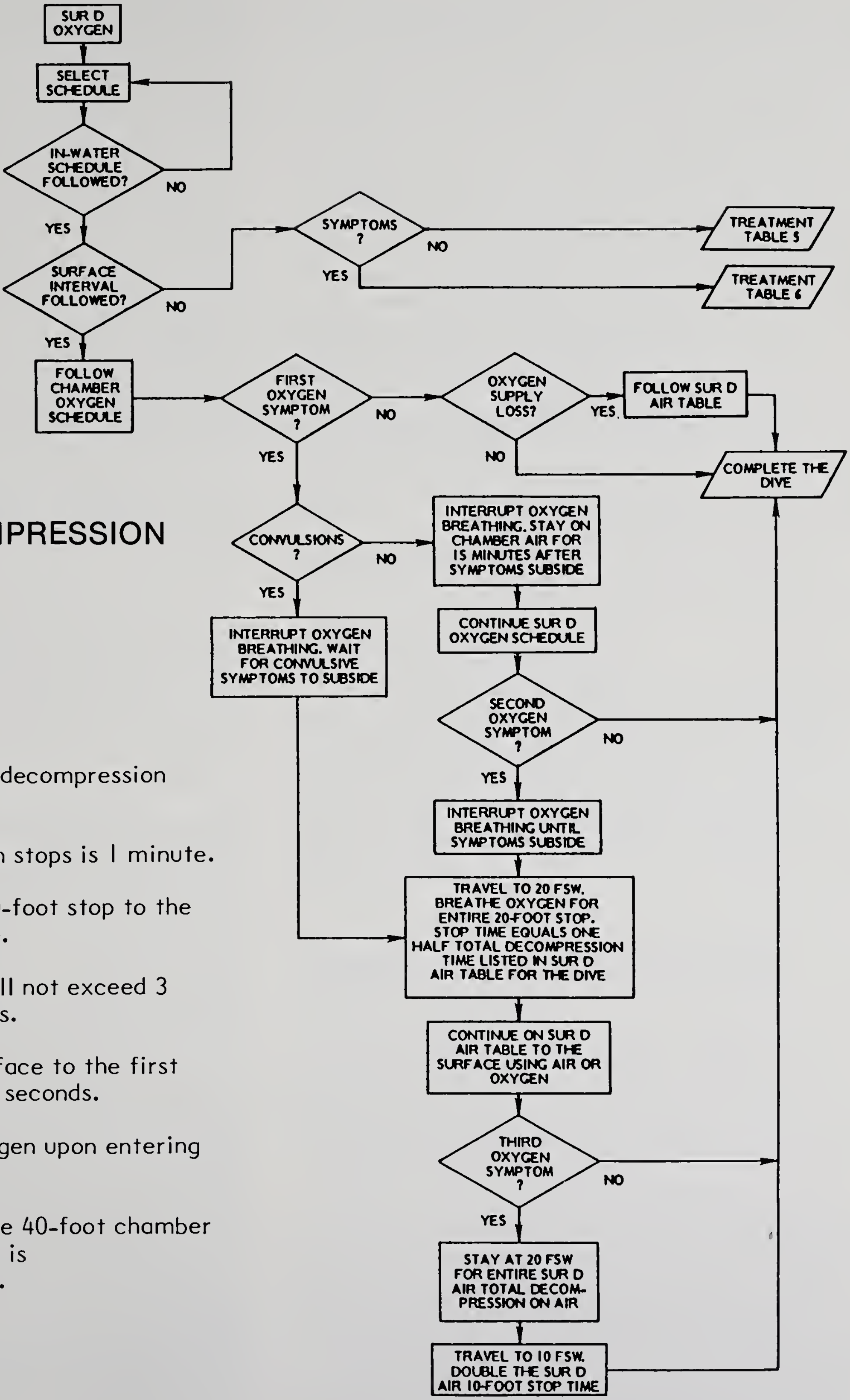
- Interrupt oxygen breathing after every 25-minute period for a 5-minute air break. Count the air breaks as dead time (that is, do not count them as part of the oxygen stop time). If the time of the air break occurs during the time the chamber is moving, the divers should be kept on oxygen and the chamber should continue to travel. This procedure simplifies timekeeping and should be used whenever the Surface Decompression Table Using Oxygen is in use. See Figure B-4 for an example.

- If the oxygen breathing system fails, the divers should be decompressed in accordance with the Surface Decompression Table Using Air, and all time spent breathing oxygen should be disregarded. Because oxygen breathing systems occasionally fail, the chamber operator should be familiar with the appropriate schedule of the Surface Decompression Table Using Air.

- If a diver exhibits signs of oxygen poisoning, he or she should be taken off oxygen breathing and should breathe air until 15 minutes has elapsed since the last sign of poisoning. The diver can then be put back on oxygen. If signs of oxygen poisoning develop again, take the diver off oxygen and, after all signs and symptoms have subsided, travel the chamber to 20 fsw (6.1 m) and shift straight across to the appropriate schedule of the Surface Decompression Table Using Air. When using this table, no credit is given for the time the diver spent at 40 fsw (12.2 m). Stop at 20 fsw (6.1 m) even if the appropriate Surface Decompression Table Using Air has no 20-foot (6.1 m) stop. At 20 fsw (6.1 m), place the diver back on oxygen for one half of the total decompression time listed in the Total Decompression Time column from the appropriate schedule of the Surface Decompression Table Using Air. This procedure will compensate for the shorter water stops completed previously by the diver on the Surface Decompression Table Using Oxygen. On completion of the required time at 20 fsw (6.1 m) with the diver breathing oxygen, follow the appropriate Surface Decompression Table Using Air schedule to the surface with the diver breathing either oxygen or air.

Example: Divers make a planned dive to 160 fsw (48 m) for 40 minutes using the Surface Decompression Table Using Oxygen. The appropriate schedule shows that there is a 3-minute water stop at 50 fsw (15.2 m), a 5-minute water stop at 40 fsw (12.2 m), an 8-minute water stop at 30 fsw (9 m), and a 32-minute chamber stop at 40 fsw (12.2 m) breathing oxygen. After 12 minutes of oxygen breathing at the 40-foot (12.2 m) chamber stop, one of the divers exhibits signs of oxygen toxicity that subside completely within 5 minutes. After an additional 15 minutes, the diver is placed back on oxygen breathing, and the decompression schedule is continued from the point of interruption. After another 10 minutes on oxygen, the same diver has a recurrence of oxygen poisoning, which again subsides completely within 5 minutes. What procedures should be followed in this situation?

Figure B-4
Surface Decompression Using Oxygen Flowchart



SURFACE DECOMPRESSION USING OXYGEN

NOTES:

1. Ascent rate to first decompression stop is 25 fpm.
2. Travel time between stops is 1 minute.
3. Travel time from 30-foot stop to the surface is 1 minute.
4. Surface interval shall not exceed 3 minutes, 30 seconds.
5. Travel from the surface to the first chamber stop is 30 seconds.
6. Begin breathing oxygen upon entering chamber.
7. Travel time from the 40-foot chamber stop to the surface is 2 minutes (20 fpm).

Source: U.S. Navy (1988)

Solution: Travel the chamber to 20 fsw (6.1 m) and shift straight across to the 160/40 schedule of the Surface Decompression Table Using Air. The total decompression time on this schedule is 98 minutes and 50 seconds. The time the diver must spend at the 20-foot (6.1 m) stop on oxygen is half of that time: 49 minutes 25 seconds. This time is then rounded up to 50 minutes. After completing 50 minutes of oxygen breathing at the 20-foot (6.1 m) stop, follow the 160/40 schedule of the Surface Decompression Table Using Air to the surface while the diver is breathing either oxygen or air.

If the diver has another episode of oxygen poisoning at the 20-foot (6.1 m) stop, or if the chamber's oxygen system fails, stay at 20 fsw (6.1 m) for the full time listed in the Total Decompression Time column of the appropriate schedule of the Surface Decompression Table Using Air, and then double the time required at the 10-foot (3 m) stop and come up the rest of the way with the diver breathing air.

Example: On the 160/40 schedule, a diver has a third episode of oxygen poisoning after 15 minutes at the 20-foot (6.1 m) stop. What procedures should be followed?

Solution: The time the diver must now stay at the 20-foot (6.1 m) stop is 98 minutes 50 seconds, which is rounded up to 99 minutes, and the time required at the 10-foot (3 m) stop is 39 minutes doubled, or 78 minutes. The time already spent by the diver at 20 fsw (6.1 m) on oxygen counts toward completion of the stop time. If oxygen breathing at the 40-foot (12.2 m) stop is interrupted and then resumed, the time the diver spent off oxygen is counted as dead time.

If oxygen poisoning occurring at the 40-foot (12.2 m) stop progresses to a convulsion, oxygen breathing must not be restarted at 40 feet (12.2 m). In this case, the chamber depth is held constant until the convulsion has subsided and the diver has regained consciousness. The chamber is then brought to 20 fsw (6.1 m), the diver is put back on oxygen breathing, and the diver is then decompressed on the appropriate schedule of the Surface Decompression Table Using Air, as described above.

Example: A diver dives to 136 feet (41 m) for 62 minutes. What is the correct schedule to use from the Surface Decompression Table Using Oxygen?

Solution: The correct decompression schedule is the 140/65 schedule. This decompression profile is illustrated in Figure B-5. Figure B-6 is an example of a dive chart for this dive.

There are no repetitive diving tables or surface interval tables for surface decompression dives. If another surface decompression dive using oxygen is planned within a 12-hour period, the following procedures apply: sum the bottom times of all dives made to get an adjusted bottom time and use the adjusted bottom time and the maximum depth attained in the previous 12 hours to select the appropriate decompression schedule.

Example: A dive is conducted to 170 fsw (51 m) for 25 minutes, has a surface interval of 3 hours 42 minutes, and is followed by a repetitive dive to 138 fsw (42 m) for 15 minutes. The Surface Decompression Table Using Oxygen is followed for both dives. What is the correct schedule?

Solution: The correct decompression schedule is 170/25 for the first dive and 170/40 for the second dive. Even though the second dive was to a maximum depth of 138 fsw (42 m) for 15 minutes, the diver must be decompressed in accordance with the maximum depth ever attained in the previous 12 hours, which was 170 fsw (51 m), and with the sum of all bottom times, which equals 40 minutes. Figure B-7 charts this example.

This example shows that, even if the second dive is a standard air dive: (1) all bottom times must be added together to get an adjusted bottom time; and (2) the decompression schedule must be selected in accordance with the maximum depth attained in the previous 12 hours.

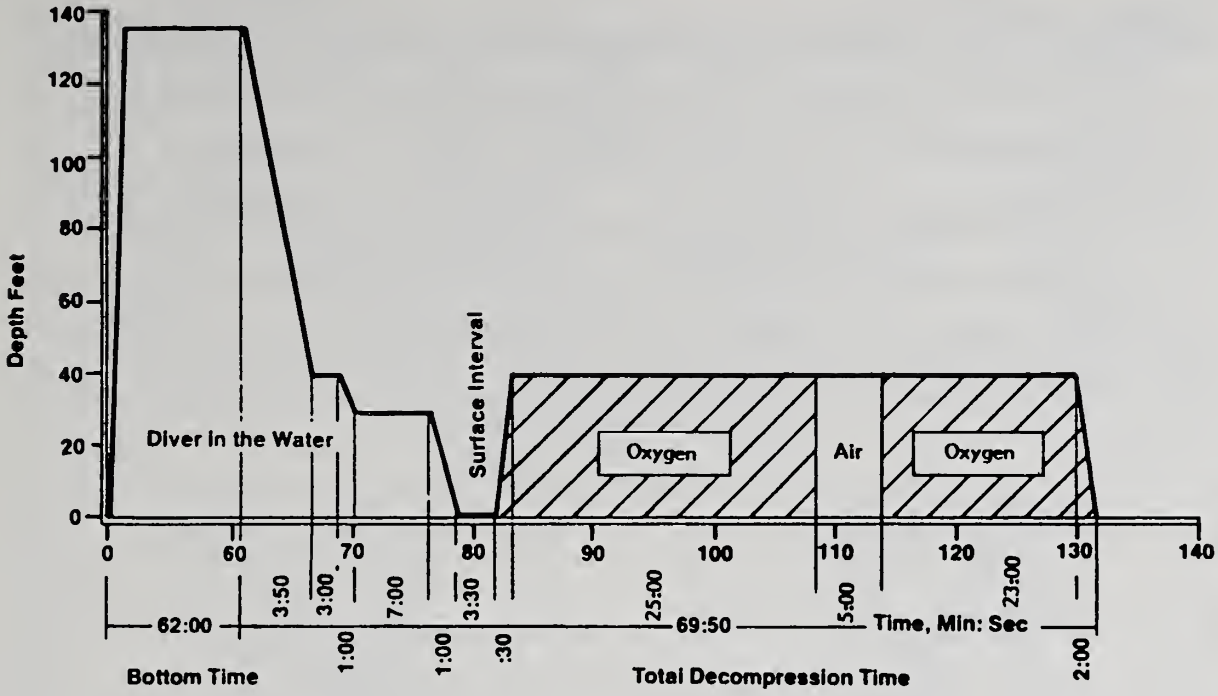
Surface Decompression Table Using Air

The Surface Decompression Table Using Air should be used for surface decompressions after air dives when no recompression chamber with an oxygen breathing system is available.

The total ascent times of the schedules in the Surface Decompression Table Using Air exceed those in the Standard Air Decompression Table; the only advantage of using the Surface Decompression Table Using Air is that it permits a diver to be kept in a controlled, closely observed environment during decompression. When employing the Surface Decompression Table Using Air, the divers should ascend from the last water stop at 60 fpm (18.3 mpm). The total elapsed time for these procedures **must not exceed 5 minutes**.

If the prescribed surface interval of 5 minutes has been exceeded and the divers are asymptomatic, they are treated as if they had Type I decompression sickness symptoms. If the divers are symptomatic, they are treated as if they had Type II decompression sickness symptoms. Symptoms occurring during chamber stops are treated as decompression sickness recurrences.

Figure B-5
Dive Profile for Surface Decompression Using Oxygen



Source: U.S. Navy (1988)

Example: What schedule would be appropriate for a dive conducted to 128 fsw (39 m) for 48 minutes using the Surface Decompression Table Using Air?

Solution: The correct decompression schedule for a dive conducted to 128 feet (39 m) for 48 minutes is the 130/50 schedule. The decompression chart is shown in Figure B-8. If a second surface decompression air dive is planned within a 12-hour period, the same rule applies for making a second surface decompression air dive as for a second surface decompression oxygen dive.

Example: A repetitive surface decompression air dive is planned to 143 fsw (43 m) for 20 minutes. The previous dive was to 172 fsw (52 m) for 30 minutes. The surface interval was 4 hours 27 minutes. What is the appropriate schedule?

Solution: The correct schedule for the first dive is 180/30; for the second dive it is 180/50. As explained in the section on the Surface Decompression Table Using Oxygen, the correct procedure is to decompress the divers on a schedule that reflects the maximum depth attained and the sum of the bottom times of all dives made in the previous 12 hours. In this example, the divers could make a third surface decompression air dive as long as the maximum depth of such a dive did not exceed 190 fsw (57 m) and the bottom time did not exceed 10 minutes. They would then be decompressed on the 190/60 schedule of the Surface Decompression Table Using Air.

Exceptional Exposure Dives

Use of the exceptional exposure air decompression schedules shown in the Standard Air Decompression Table is discouraged because decompressions conducted in accordance with these schedules are likely to result in decompression sickness. Accordingly, exceptional exposure dives should be conducted only in an emergency and then only with the consent of the NOAA Diving Coordinator.

GENERAL USE OF DECOMPRESSION

Rules During Ascent

After the correct decompression schedule has been selected, it is imperative that it be followed exactly. Decompression must be completed in accordance with the selected schedule unless a deviation has been approved by the NOAA Diving Coordinator.

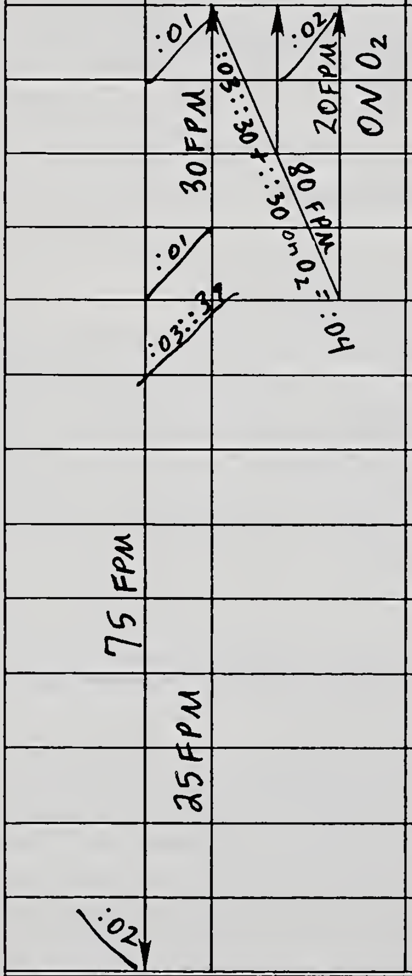
Ascend at a rate of 60 fpm (18.3 m/min) when using tables other than the Surface Decompression Table Using Oxygen. (This table uses a rate of 25 fpm (7.5 mpm).) Any variation in the rate of ascent must be corrected in accordance with the procedures described below in the Variations in Rate of Ascent section.

Decompression stop depths should be measured from the level of the diver's chest. Decompression stop times are counted from the time the diver reaches the stop

Figure B-6
Dive Chart for Dive Involving Surface Decompression Using Oxygen

DIVING CHART - AIR

DATE 02 MAY 88			
NAME OF DIVER 1 DEVLIN	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) —
NAME OF DIVER 2 MOEBIUS	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) —
TENDERS (DIVER 1) COX AND NEAL		TENDERS (DIVER 2) SLOAN AND WARREN	
LEFT SURFACE (LS) 1200	DEPTH (fsw) 131 + 5 = 136	REACHED BOTTOM (RB) ~~1202~~	DESCENT TIME :02
LEFT BOTTOM (LB) 1302	TOTAL BOTTOM TIME (TBT) :62	TABLE & SCHEDULE USED 140/65 Sur'D' O_2	TIME TO FIRST STOP :3::39
REACHED SURFACE (RS) 1317::39/1416::39	TOTAL DECOMPRESSION TIME (TDT) 01:14::39	TOTAL TIME OF DIVE (TTD) 02:16::39	REPETITIVE GROUP None



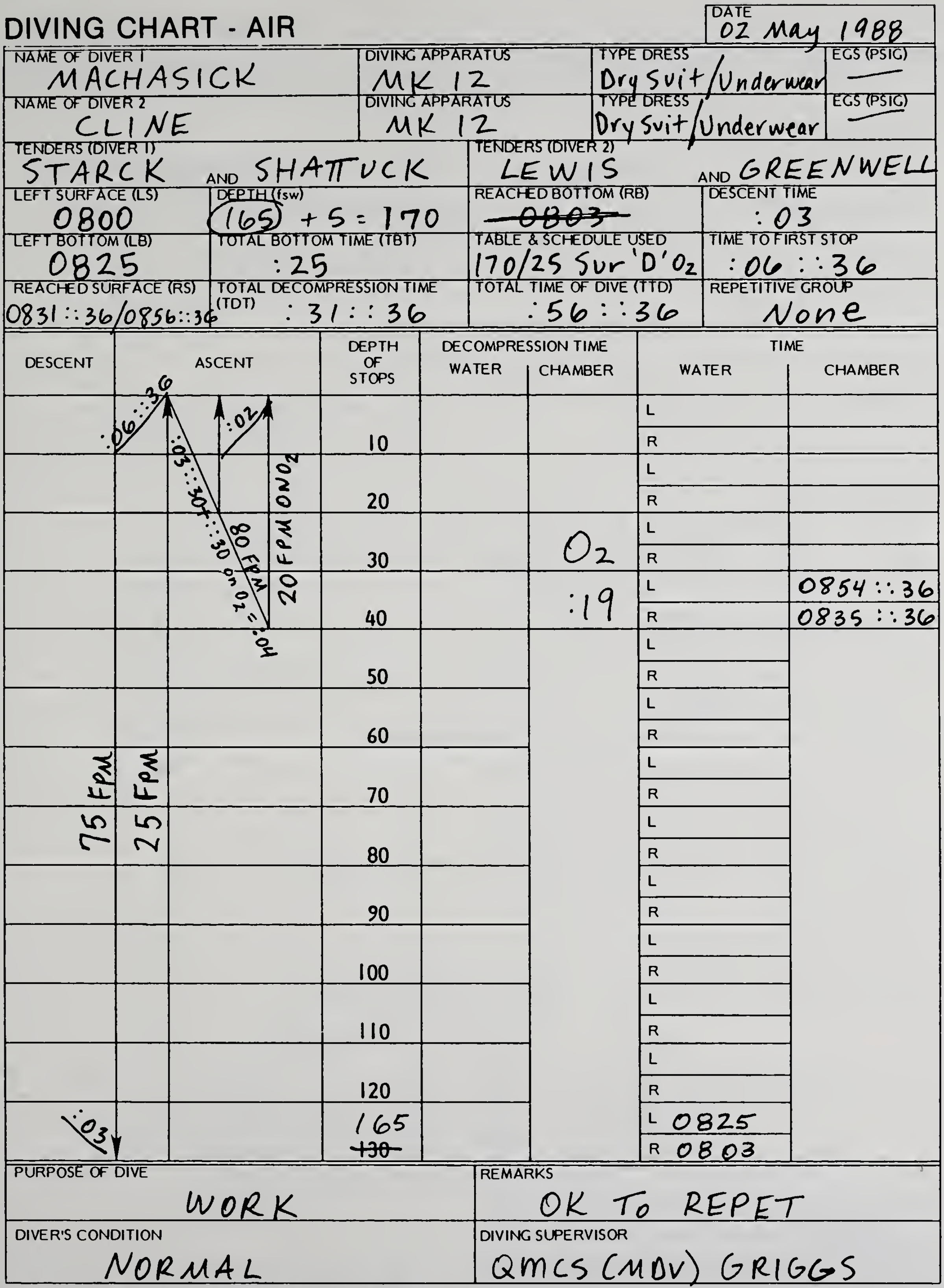
DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME WATER	DECOMPRESSION TIME CHAMBER		TIME WATER	TIME CHAMBER
		10			L		
					R		
		20			L		
					R		
		30	:07	O_2 Air O_2	L	1316::39	
					R	1309::39	
		40	:03	:25+:5+:23 :53	L	1308::39	1414::39
					R	1305::39	1321::39
		50			L		
					R		
		60			L		
					R		
		70			L		
					R		
		80			L		
					R		
		90			L		
					R		
		100			L		
					R		
		110			L		
					R		
		120			L		
					R		
		131 ~~130~~			L	1302	
					R	1202	

PURPOSE OF DIVE WORK	REMARKS OK TO REPET
DIVER'S CONDITION NORMAL	DIVING SUPERVISOR HTCM(MDV) HUSS

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

Figure B-7A
Dive Chart for Dive Involving Surface Decompression Using Oxygen



DIVING CHART - AIR

DATE: 02 May 1988

NAME OF DIVER 1 MACHASICK	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) —
NAME OF DIVER 2 CLINE	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) —

TENDERS (DIVER 1): STARCK AND SHATTUCK
TENDERS (DIVER 2): LEWIS AND GREENWELL

LEFT SURFACE (LS) 0800	DEPTH (fsw) (165) + 5 = 170	REACHED BOTTOM (RB) ~~0803~~	DESCENT TIME :03
LEFT BOTTOM (LB) 0825	TOTAL BOTTOM TIME (TBT) :25	TABLE & SCHEDULE USED 170/25 Sur 'D' O₂	TIME TO FIRST STOP :06::36
REACHED SURFACE (RS) 0831::36/0856::36	TOTAL DECOMPRESSION TIME (TDT) :31::36	TOTAL TIME OF DIVE (TTD) :56::36	REPETITIVE GROUP None

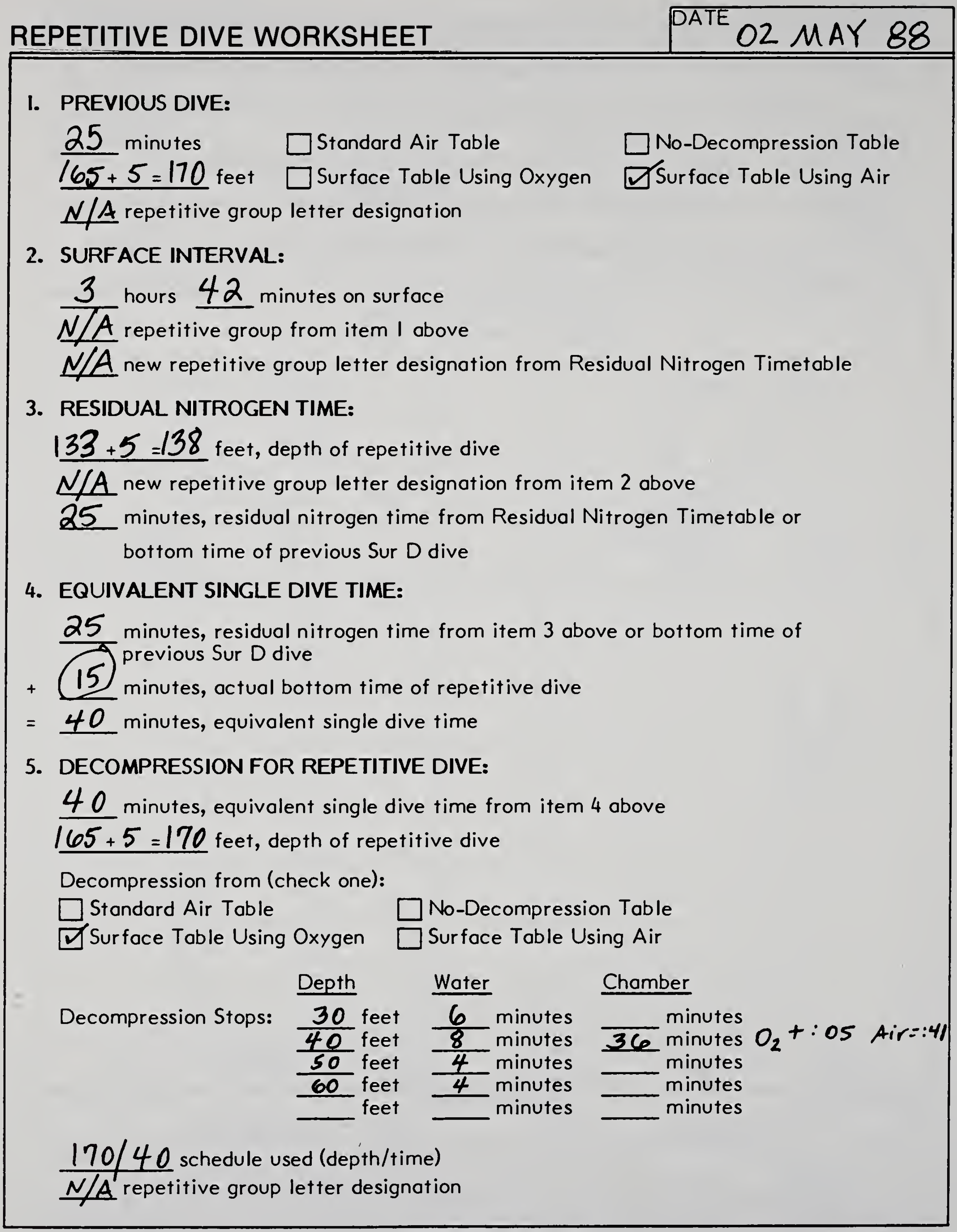
DEPTH OF STOPS	DECOMPRESSION TIME		TIME	
	WATER	CHAMBER	WATER	CHAMBER
			L	
10			R	
			L	
20			R	
			L	
30		O₂	R	
		:19	L	0854::36
40			R	0835::36
			L	
50			R	
			L	
60			R	
			L	
70			R	
			L	
80			R	
			L	
90			R	
			L	
100			R	
			L	
110			R	
			L	
120			R	
165 ~~130~~			L 0825 R 0803	

PURPOSE OF DIVE: WORK
REMARKS: OK TO REPET
DIVER'S CONDITION: NORMAL
DIVING SUPERVISOR: QMCS (MDV) GRIGGS

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

Figure B-7B
(Continued)



REPETITIVE DIVE WORKSHEET

DATE 02 MAY 88

1. PREVIOUS DIVE:

25 minutes
165 + 5 = 170 feet
N/A repetitive group letter designation

☐ Standard Air Table
☐ Surface Table Using Oxygen
☐ No-Decompression Table
☑ Surface Table Using Air

2. SURFACE INTERVAL:

3 hours 42 minutes on surface
N/A repetitive group from item 1 above
N/A new repetitive group letter designation from Residual Nitrogen Timetable

3. RESIDUAL NITROGEN TIME:

133 + 5 = 138 feet, depth of repetitive dive
N/A new repetitive group letter designation from item 2 above
25 minutes, residual nitrogen time from Residual Nitrogen Timetable or bottom time of previous Sur D dive

4. EQUIVALENT SINGLE DIVE TIME:

25 minutes, residual nitrogen time from item 3 above or bottom time of previous Sur D dive
\+ (15) minutes, actual bottom time of repetitive dive
= 40 minutes, equivalent single dive time

5. DECOMPRESSION FOR REPETITIVE DIVE:

40 minutes, equivalent single dive time from item 4 above
165 + 5 = 170 feet, depth of repetitive dive

Decompression from (check one):

☐ Standard Air Table
☑ Surface Table Using Oxygen
☐ No-Decompression Table
☐ Surface Table Using Air

	Depth	Water	Chamber	
Decompression Stops:	30 feet	6 minutes	minutes	
	40 feet	8 minutes	36 minutes	O_2 + :05 Air = :41
	50 feet	4 minutes	minutes	
	60 feet	4 minutes	minutes	
	feet	minutes	minutes	

170/40 schedule used (depth/time)
N/A repetitive group letter designation

Source: U.S. Navy (1988)

Figure B-7C
(Continued)

DIVING CHART - AIR

DATE 02 MAY 88

NAME OF DIVER 1 MACHASICK	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) —
NAME OF DIVER 2 CLINE	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) —
TENDERS (DIVER 1) STANLEY AND TROTTER		TENDERS (DIVER 2) STOKES AND VELARDE	
LEFT SURFACE (LS) 1239	DEPTH (fsw) 133 + 5 = ~~138~~/170	REACHED BOTTOM (RB) ~~1241~~	DESCENT TIME :02
LEFT BOTTOM (LB) 1254	~~TOTAL BOTTOM TIME (TBT)~~ Previous :25 + :15 = :40	TABLE & SCHEDULE USED 170/40 Sur'D'O$_2$	TIME TO FIRST STOP :02 ::56
REACHED SURFACE (RS) 1322::56/1409::56	TOTAL DECOMPRESSION TIME (TDT) 1:15::56	TOTAL TIME OF DIVE (TTD) 1:30::56	REPETITIVE GROUP None

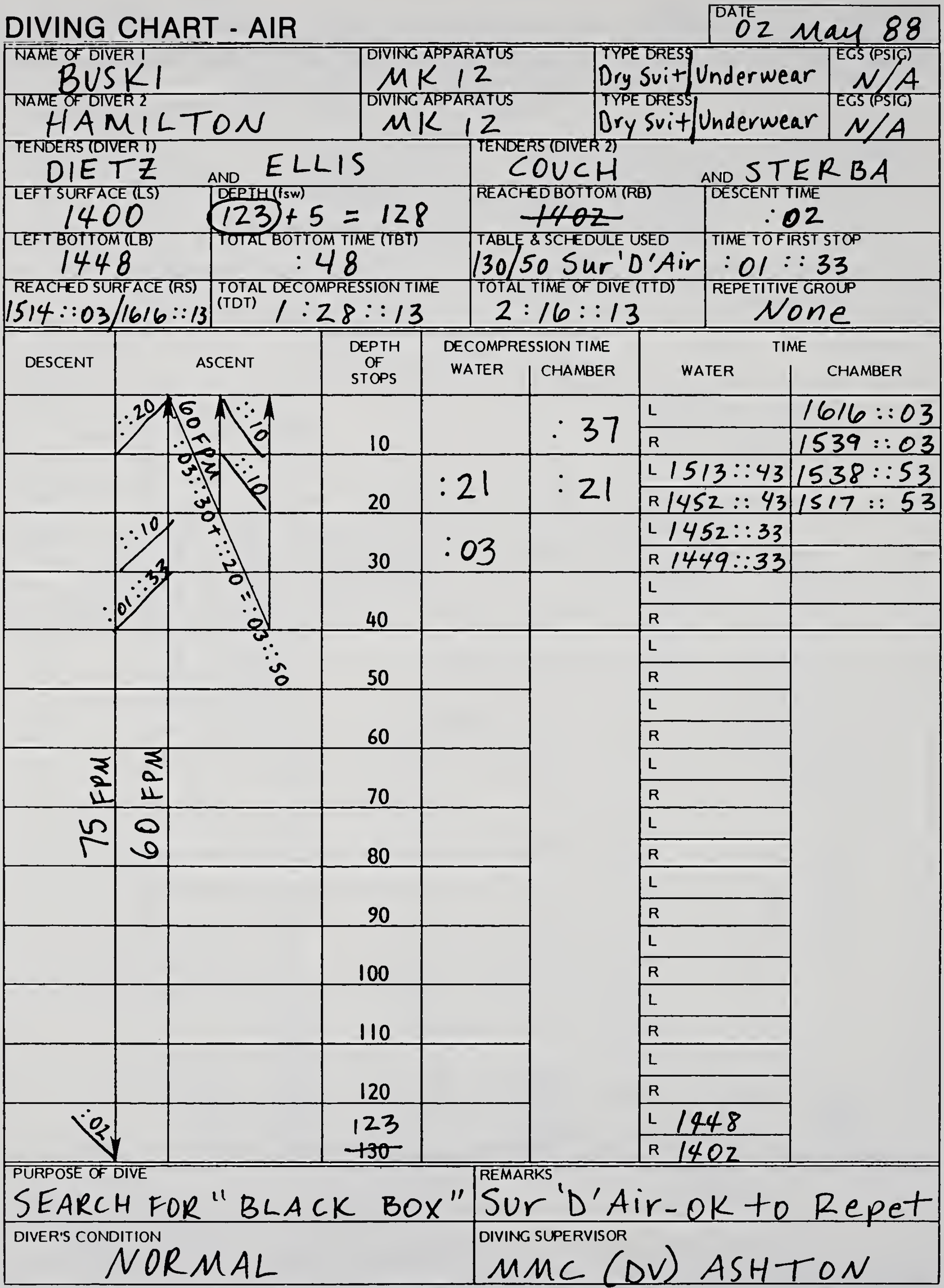
DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME		TIME	
			WATER	CHAMBER	WATER	CHAMBER
	:01 :02 :03::30+::30 on O$_2$ = :04 20 FPM on O$_2$				L	
		10			R	
	80 FPM				L	
		20			R	
					L 1321::56	
		30	:06	O$_2$ Air O$_2$	R 1315::56	
	:01			25+5+11	L 1314::56	1407::56
		40	:08	:41	R 1306::56	1326::56
	:01				L 1305::56	
		50	:04		R 1301::56	
	:01				L 1300::56	
		60	:04		R 1256::56	
	:02::56				L	
		70			R	
					L	
		80			R	
75 FPM	25 FPM				L	
		90			R	
					L	
		100			R	
					L	
		110			R	
					L	
		120			R	
:02		133			L 1254	
		~~130~~			R 1251	

PURPOSE OF DIVE WORK	REMARKS Sur DO$_2$ Limit - Do Not Repet
DIVER'S CONDITION NORMAL	DIVING SUPERVISOR HMCM (Dr) THOMAS

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

Figure B-8
Dive Chart for Dive Involving Surface Decompression Using Air



DIVING CHART - AIR

DATE 02 May 88			
NAME OF DIVER 1 BUSKI	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit / Underwear	EGS (PSIG) N/A
NAME OF DIVER 2 HAMILTON	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit / Underwear	EGS (PSIG) N/A
TENDERS (DIVER 1) DIETZ AND ELLIS		TENDERS (DIVER 2) COUCH AND STERBA	
LEFT SURFACE (LS) 1400	DEPTH (fsw) 123 + 5 = 128	REACHED BOTTOM (RB) ~~1402~~	DESCENT TIME :02
LEFT BOTTOM (LB) 1448	TOTAL BOTTOM TIME (TBT) :48	TABLE & SCHEDULE USED 130/50 Sur'D'Air	TIME TO FIRST STOP :01::33
REACHED SURFACE (RS) 1514::03/1616::13	TOTAL DECOMPRESSION TIME (TDT) 1:28::13	TOTAL TIME OF DIVE (TTD) 2:16::13	REPETITIVE GROUP None

DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME WATER	DECOMPRESSION TIME CHAMBER		TIME WATER	TIME CHAMBER
		10		:37	L		1616::03
					R		1539::03
		20	:21	:21	L	1513::43	1538::53
					R	1452::43	1517::53
		30	:03		L	1452::33	
					R	1449::33	
		40			L		
					R		
		50			L		
					R		
		60			L		
					R		
		70			L		
					R		
		80			L		
					R		
		90			L		
					R		
		100			L		
					R		
		110			L		
					R		
		120			L		
					R		
		123 ~~130~~			L	1448	
					R	1402	

PURPOSE OF DIVE SEARCH FOR "BLACK BOX"	REMARKS Sur'D'Air-OK to Repet
DIVER'S CONDITION NORMAL	DIVING SUPERVISOR MMC (DV) ASHTON

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

depth. On completion of the specified stop time, the divers ascend to the next stop or to the surface at the designated ascent rate. **Ascent time is not counted as part of stop time.**

Variations in Rate of Ascent

Since conditions sometimes prevent prescribed ascent rates from being maintained, a general set of instructions has been established to compensate for any variations in rate of ascent. These instructions, along with examples of their application, are listed below:

If the rate of ascent is less than 60 fpm (18.3 m/min) and the delay occurs deeper than 50 fsw (15.2 m), add the total delay time to the bottom time, recompute a new decompression schedule, and decompress accordingly.

Example: A dive was conducted to 120 fsw (36 m) with a bottom time of 60 minutes. According to the 120/60 decompression schedule of the Standard Air Decompression Table, the first decompression stop is at 30 feet (9 m). During ascent, the divers were delayed at 100 fsw (33 m) and it actually took 4 minutes 55 seconds to reach the 30-foot (9 m) decompression stop. What schedule should be used to determine the diver's decompression requirements?

Solution: If an ascent rate of 60 fpm (18.3 m/min) had been used, it would have taken the diver 1 minute 30 seconds to ascend from 120 fsw (40 m) to 30 fsw (9 m). The difference between the actual and 60 fpm (18.3 m/min) ascent times is 3 minutes 30 seconds. To compensate, increase the bottom time of the dive from 60 minutes to 63 minutes 30 seconds and continue decompression according to the schedule that reflects this new bottom time, which is the 120/70 schedule. (Note from the Standard Air Decompression Table that this 3-minute 30-second delay increased the diver's total decompression time from 71 minutes to 89 minutes—an increase of 18 minutes (Figure B-9).)

If the rate of ascent is less than 60 fpm (18.3 m/min) and the delay occurs shallower than 50 fsw (15 m), add the total delay time to the diver's first decompression stop.

Example: A dive was conducted to 120 feet (40 m) with a bottom time of 60 minutes. As shown in the Standard Air Decompression Table, the first decompression stop is at 30 fsw (9 m). During the ascent, the divers were delayed at 40 feet (12.2 m) and it actually took 5 minutes for them to reach the 30-foot (9 m) stop. How much time does the diver need to spend at the first stop?

Solution: As in the preceding example, the correct ascent time should have been 1 minute 30 seconds, but the diver was delayed by 3 minutes 30 seconds. To compensate, increase the length of the 30-foot (9 m) decompression stop by 3 minutes 30 seconds. This means that, instead of 2 minutes, the divers must spend 5 minutes 30 seconds at 30 feet (9 m). (Note that in this example the diver's total decompression time is increased by only 7 minutes: the 3-minute 30-second delay in ascent plus the additional 3 minutes 30 seconds they had to spend at 30 feet (9 m) (Figure B-10).)

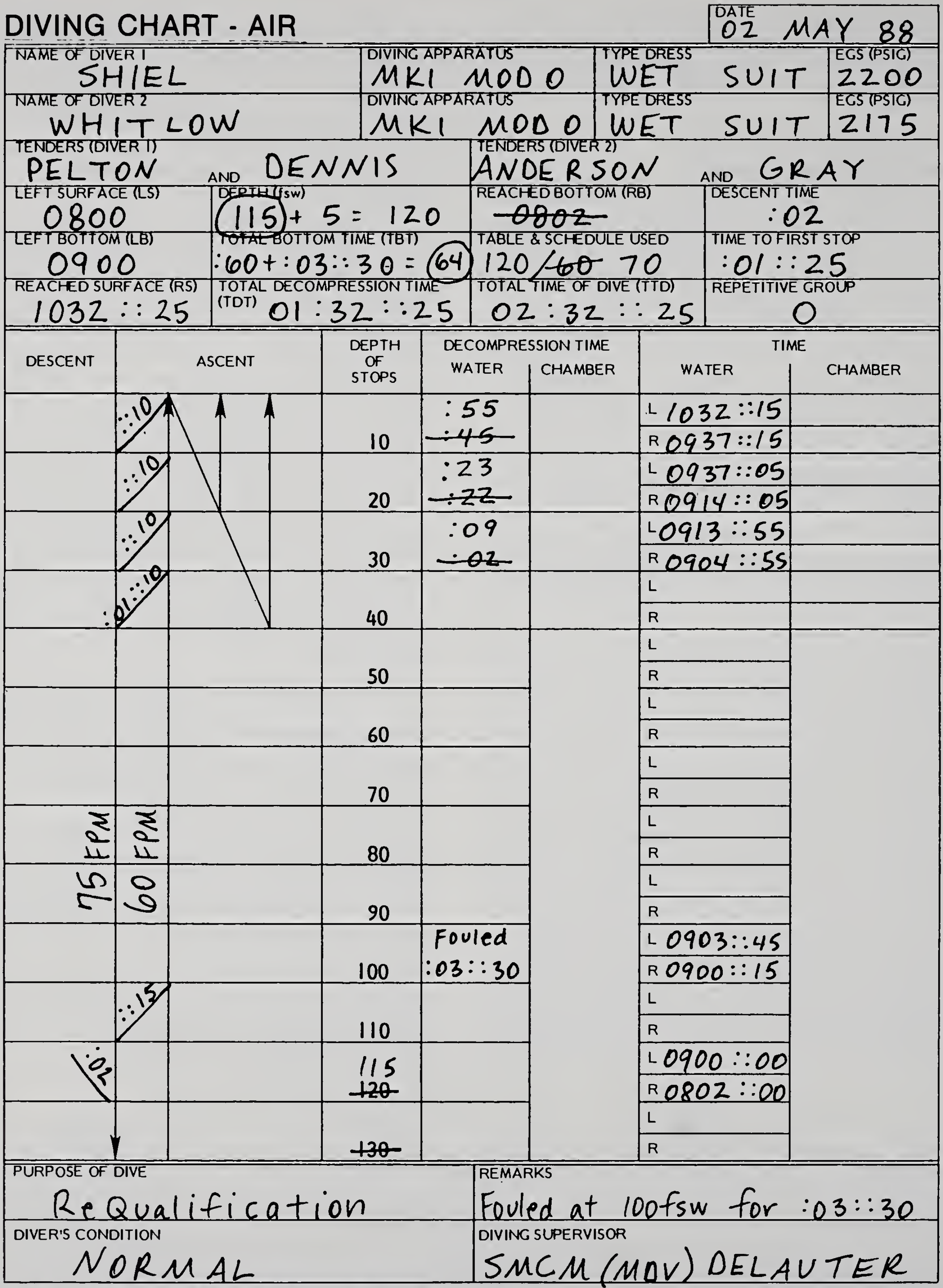
If the rate of ascent is greater than 60 fpm (18.3 m/min) during a dive in which no decompression is required, either slow the rate of ascent to allow the watches to catch up or stop at 10 fsw (3 m) for an amount of time equal to the difference between the length of time the ascent should have taken and the time it actually took.

Example: A dive was conducted to 100 fsw (33 m) with a bottom time of 22 minutes. During ascent, the diver momentarily lost control of his or her buoyancy, which increased the ascent rate so that the diver reached 10 feet (3 m) in 1 minute 15 seconds. How will this influence the diver's decompression?

Solution: At a rate of 60 fpm (18.3 m/min), the ascent should take 1 minute 25 seconds to reach the 10-foot (3 m) stop. The diver must remain at 10 feet (3 m) for the difference between 1 minute 25 seconds and 1 minute 15 seconds, or an additional stop time of 10 seconds (Figure B-11).

If the rate of ascent is greater than 60 fpm (18.3 m/min) during a dive that requires decompression, stop 10 feet (3 m) below the first decompression stop and allow the watches to catch up.

Figure B-9
Dive Chart for Decompression Dive; Delay Deeper Than 50 fsw



DIVING CHART - AIR

DATE 02 MAY 88

NAME OF DIVER 1 SHIEL	DIVING APPARATUS MKI MOD 0	TYPE DRESS WET SUIT	EGS (PSIG) 2200
NAME OF DIVER 2 WHITLOW	DIVING APPARATUS MKI MOD 0	TYPE DRESS WET SUIT	EGS (PSIG) 2175
TENDERS (DIVER 1) PELTON AND DENNIS		TENDERS (DIVER 2) ANDERSON AND GRAY	
LEFT SURFACE (LS) 0800	DEPTH (fsw) 115 + 5 = 120	REACHED BOTTOM (RB) ~~0802~~	DESCENT TIME :02
LEFT BOTTOM (LB) 0900	TOTAL BOTTOM TIME (TBT) :60 + :03::30 = 64	TABLE & SCHEDULE USED 120/~~60~~ 70	TIME TO FIRST STOP :01::25
REACHED SURFACE (RS) 1032::25	TOTAL DECOMPRESSION TIME (TDT) 01:32::25	TOTAL TIME OF DIVE (TTD) 02:32::25	REPETITIVE GROUP O

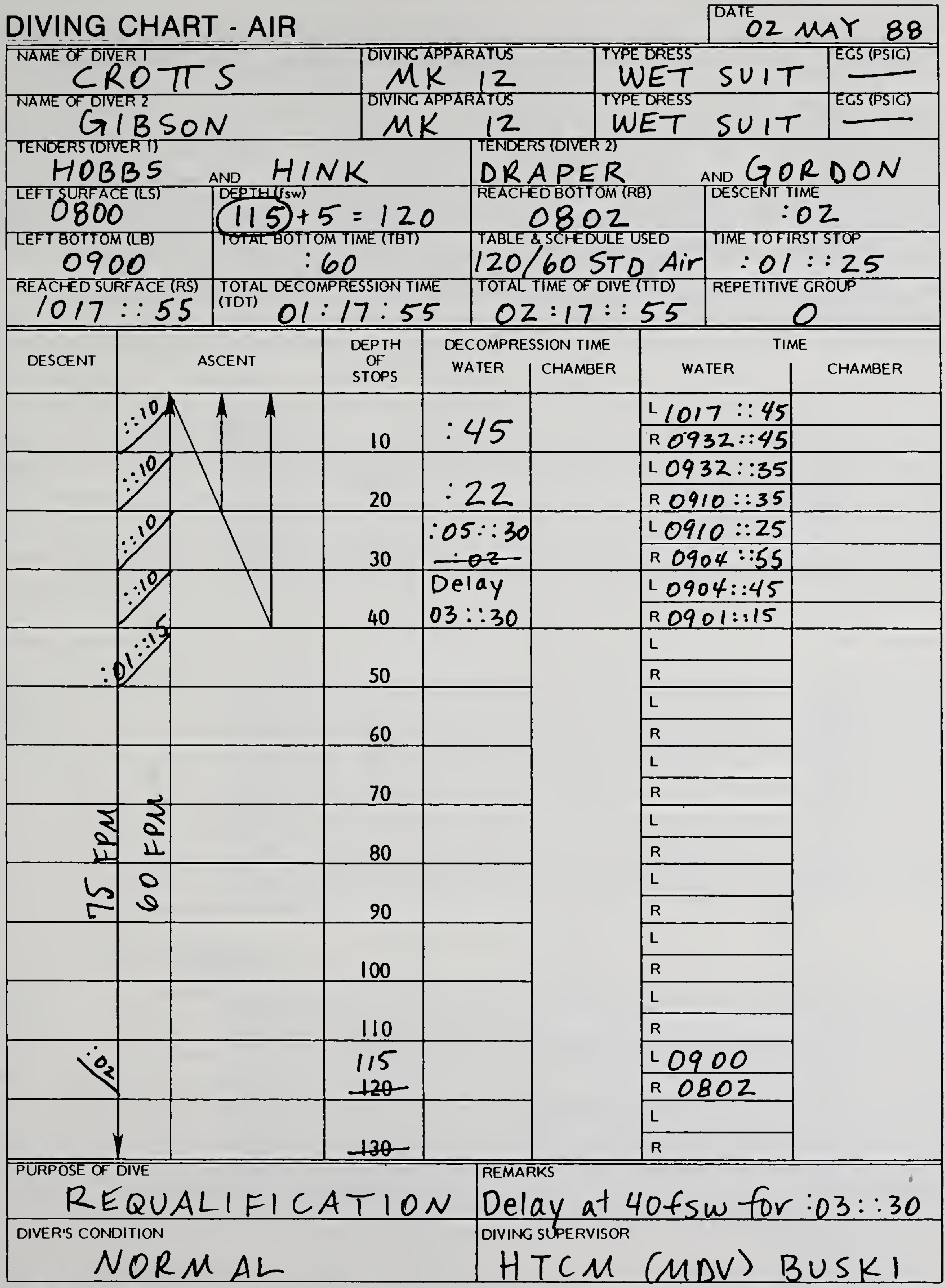
DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME WATER	DECOMPRESSION TIME CHAMBER	TIME WATER	TIME CHAMBER
		10	:55 ~~:45~~		L 1032::15 R 0937::15	
		20	:23 ~~:22~~		L 0937::05 R 0914::05	
		30	:09 ~~:02~~		L 0913::55 R 0904::55	
		40			L R	
		50			L R	
		60			L R	
		70			L R	
		80			L R	
		90			L R	
		100	Fouled :03::30		L 0903::45 R 0900::15	
		110			L R	
		115 ~~120~~			L 0900::00 R 0802::00	
		~~130~~			L R	

PURPOSE OF DIVE ReQualification	REMARKS Fouled at 100fsw for :03::30
DIVER'S CONDITION NORMAL	DIVING SUPERVISOR SMCM (MDV) DELAUTER

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

Figure B-10
Dive Chart for Decompression Dive; Delay Less Than 50 fsw



DIVING CHART - AIR

DATE 02 MAY 88

NAME OF DIVER 1 CROTTS	DIVING APPARATUS MK 12	TYPE DRESS WET SUIT	EGS (PSIG) —
NAME OF DIVER 2 GIBSON	DIVING APPARATUS MK 12	TYPE DRESS WET SUIT	EGS (PSIG) —
TENDERS (DIVER 1) HOBBS AND HINK		TENDERS (DIVER 2) DRAPER AND GORDON	
LEFT SURFACE (LS) 0800	DEPTH (fsw) 115+5 = 120	REACHED BOTTOM (RB) 0802	DESCENT TIME :02
LEFT BOTTOM (LB) 0900	TOTAL BOTTOM TIME (TBT) :60	TABLE & SCHEDULE USED 120/60 STD Air	TIME TO FIRST STOP :01::25
REACHED SURFACE (RS) 1017::55	TOTAL DECOMPRESSION TIME (TDT) 01:17:55	TOTAL TIME OF DIVE (TTD) 02:17::55	REPETITIVE GROUP O

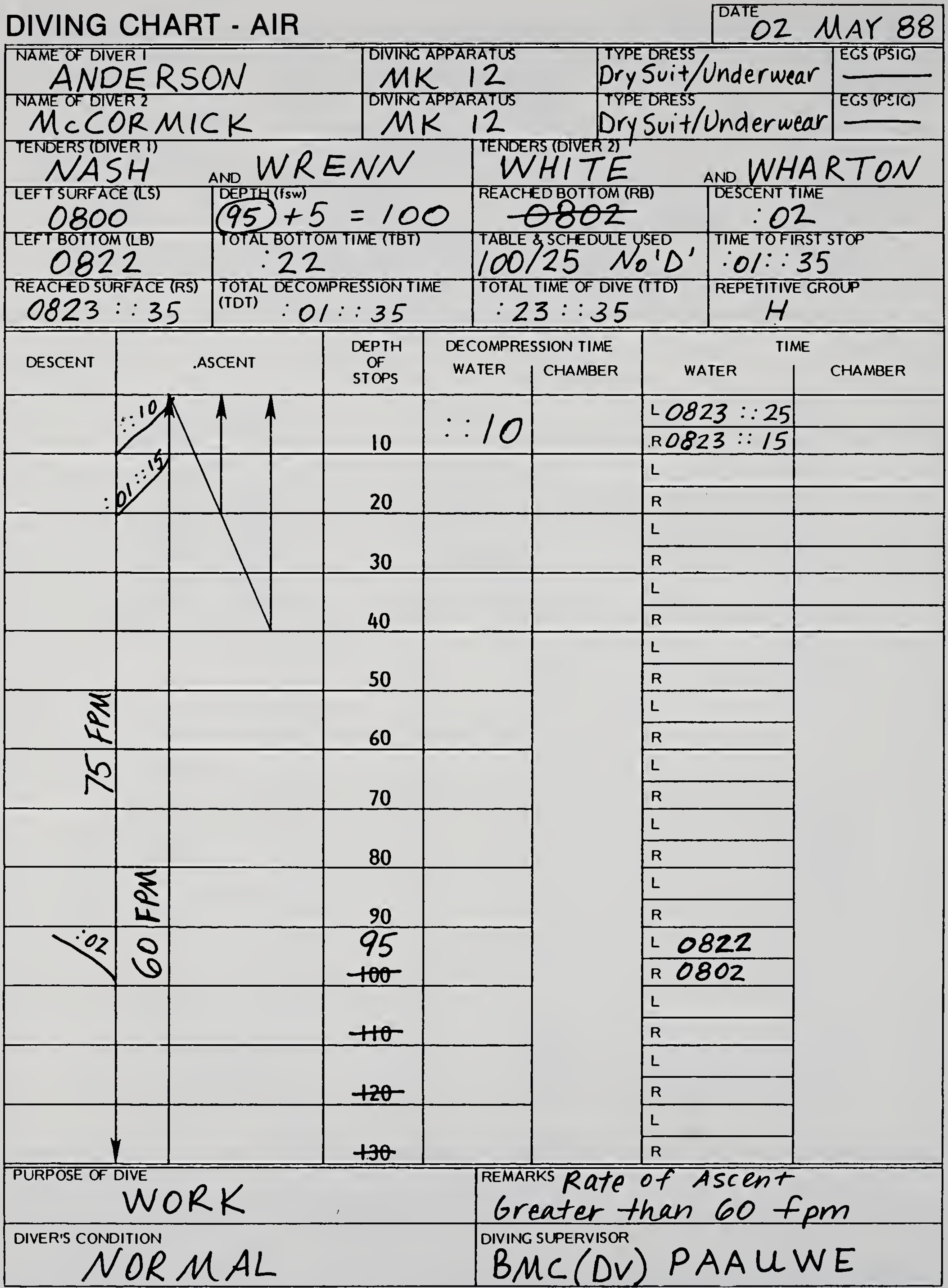
DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME WATER	DECOMPRESSION TIME CHAMBER	TIME WATER	TIME CHAMBER
	::10	10	:45		L 1017::45 R 0932::45	
	::10	20	:22		L 0932::35 R 0910::35	
	::10	30	:05::30 ~~:02~~		L 0910::25 R 0904::55	
	::10	40	Delay 03::30		L 0904::45 R 0901::15	
	:01::15	50			L R	
		60			L R	
		70			L R	
75 FPM	60 FPM	80			L R	
		90			L R	
		100			L R	
		110			L R	
:02		115 ~~120~~			L 0900 R 0802	
		~~130~~			L R	

PURPOSE OF DIVE REQUALIFICATION	REMARKS Delay at 40fsw for :03::30
DIVER'S CONDITION NORMAL	DIVING SUPERVISOR HTCM (MDV) BUSKI

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

Figure B-11
No-Decompression Dive; Rate of Ascent Greater than 60 fpm



DIVING CHART - AIR

DATE 02 MAY 88

NAME OF DIVER 1 ANDERSON	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) ——
NAME OF DIVER 2 McCORMICK	DIVING APPARATUS MK 12	TYPE DRESS Dry Suit/Underwear	EGS (PSIG) ——
TENDERS (DIVER 1) NASH AND WRENN		TENDERS (DIVER 2) WHITE AND WHARTON	
LEFT SURFACE (LS) 0800	DEPTH (fsw) 95 +5 = 100	REACHED BOTTOM (RB) ~~0802~~	DESCENT TIME :02
LEFT BOTTOM (LB) 0822	TOTAL BOTTOM TIME (TBT) :22	TABLE & SCHEDULE USED 100/25 No 'D'	TIME TO FIRST STOP :01::35
REACHED SURFACE (RS) 0823::35	TOTAL DECOMPRESSION TIME (TDT) :01::35	TOTAL TIME OF DIVE (TTD) :23::35	REPETITIVE GROUP H

DESCENT	ASCENT	DEPTH OF STOPS	DECOMPRESSION TIME WATER	DECOMPRESSION TIME CHAMBER	TIME WATER	TIME CHAMBER
		10	::10		L 0823::25	
					R 0823::15	
		20			L	
					R	
		30			L	
					R	
		40			L	
					R	
		50			L	
					R	
		60			L	
					R	
		70			L	
					R	
		80			L	
					R	
		90			L	
					R	
		95 ~~100~~			L 0822	
					R 0802	
		~~110~~			L	
					R	
		~~120~~			L	
					R	
		~~130~~			L	
					R	

PURPOSE OF DIVE WORK	REMARKS Rate of Ascent Greater than 60 fpm
DIVER'S CONDITION NORMAL	DIVING SUPERVISOR BMC(DV) PAAUWE

Note: In this example, travel time is shown in seconds. For most diving operations, however, recording the travel time in minutes is sufficient.

Source: U.S. Navy (1988)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

Depth (feet)	Bottom time (min)	Time first stop (min:sec)	Decompression stops (feet)					Total decompression time (min:sec)	Repetitive group
			50	40	30	20	10		
40	200						0	0:40	*
	210	0:30					2	2:40	N
	230	0:30					7	7:40	N
	250	0:30					11	11:40	O
	270	0:30					15	15:40	O
	300	0:30					19	19:40	Z
	360	0:30					23	23:40	**
	480	0:30					41	41:40	**
	720	0:30					69	69:40	**
50	100						0	0:50	*
	110	0:40					3	3:50	L
	120	0:40					5	5:50	M
	140	0:40					10	10:50	M
	160	0:40					21	21:50	N
	180	0:40					29	29:50	O
	200	0:40					35	35:50	O
	220	0:40					40	40:50	Z
	240	0:40					47	47:50	Z
60	60						0	1:00	*
	70	0:50					2	3:00	K
	80	0:50					7	8:00	L
	100	0:50					14	15:00	M
	120	0:50					26	27:00	N
	140	0:50					39	40:00	O
	160	0:50					48	49:00	Z
	180	0:50					56	57:00	Z
	200	0:40				1	69	71:00	Z
	240	0:40				2	79	82:00	**
	360	0:40				20	119	140:00	**
	480	0:40				44	148	193:00	**
	720	0:40				78	187	266:00	**
70	50						0	1:10	*
	60	1:00					8	9:10	K
	70	1:00					14	15:10	L
	80	1:00					18	19:10	M
	90	1:00					23	24:10	N
	100	1:00					33	34:10	N
	110	0:50				2	41	44:10	O
	120	0:50				4	47	52:10	O
	130	0:50				6	52	59:10	O
	140	0:50				8	56	65:10	Z
	150	0:50				9	61	71:10	Z
	160	0:50				13	72	86:10	Z
	170	0:50				19	79	99:10	Z

***See No Decompression Table for repetitive groups**
****Repetitive dives may not follow exceptional exposure dives**

Source: U.S. Navy (1988)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

Depth (feet)	Bottom time (min)	Time first stop (min:sec)	Decompression stops (feet)					Total decompression time (min:sec)	Repetitive group
			50	40	30	20	10		
80	40						0	1:20	*
	50	1:10					10	11:20	K
	60	1:10					17	18:20	L
	70	1:10					23	24:20	M
	80	1:00				2	31	34:20	N
	90	1:00				7	39	47:20	N
	100	1:00				11	46	58:20	O
	110	1:00				13	53	67:20	O
	120	1:00				17	56	74:20	Z
	130	1:00				19	63	83:20	Z
	140	1:00				26	69	96:20	Z
	150	1:00				32	77	110:20	Z
	180	1:00				35	85	121:20	**
	240	0:50			6	52	120	179:20	**
	360	0:50			29	90	160	280:20	**
	480	0:50			59	107	187	354:20	**
	720	0:40		17	108	142	187	455:20	**
90	30						0	1:30	*
	40	1:20					7	8:30	J
	50	1:20					18	19:30	L
	60	1:20					25	26:30	M
	70	1:10				7	30	38:30	N
	80	1:10				13	40	54:30	N
	90	1:10				18	48	67:30	O
	100	1:10				21	54	76:30	Z
	110	1:10				24	61	86:30	Z
	120	1:10				32	68	101:30	Z
	130	1:00			5	36	74	116:30	Z
100	25						0	1:40	*
	30	1:30					3	4:40	I
	40	1:30					15	16:40	K
	50	1:20				2	24	27:40	L
	60	1:20				9	28	38:40	N
	70	1:20				17	39	57:40	O
	80	1:20				23	48	72:40	O
	90	1:10			3	23	57	84:40	Z
	100	1:10			7	23	66	97:40	Z
	110	1:10			10	34	72	117:40	Z
	120	1:10			12	41	78	132:40	Z
	180	1:00		1	29	53	118	202:40	**
	240	1:00		14	42	84	142	283:40	**
	360	0:50	2	42	73	111	187	416:40	**
	480	0:50	21	61	91	142	187	503:40	**
	720	0:50	55	106	122	142	187	613:40	**
110	20						0	1:50	*
	25	1:40					3	4:50	H
	30	1:40					7	8:50	J
	40	1:30				2	21	24:50	L
	50	1:30				8	26	35:50	M
	60	1:30				18	36	55:50	N
	70	1:20			1	23	48	73:50	O
	80	1:20			7	23	57	88:50	Z
	90	1:20			12	30	64	107:50	Z
	100	1:20			15	37	72	125:50	Z

*See No Decompression Table for repetitive groups

**Repetitive dives may not follow exceptional exposure dives

Source: U.S. Navy (1988)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet) 70	60	50	40	30	20	10	Total decompression time (min:sec)	Repeti-tive group
120	15								0	2:00	*
	20	1:50							2	4:00	H
	25	1:50							6	8:00	I
	30	1:50							14	16:00	J
	40	1:40						5	25	32:00	L
	50	1:40						15	31	48:00	N
	60	1:30					2	22	45	71:00	O
	70	1:30					9	23	55	89:00	O
	80	1:30					15	27	63	107:00	Z
	90	1:30					19	37	74	132:00	Z
	100	1:30					23	45	80	150:00	Z
	120	1:20				10	19	47	98	176:00	**
	180	1:10			5	27	37	76	137	284:00	**
	240	1:10			23	35	60	97	179	396:00	**
	360	1:00		18	45	64	93	142	187	551:00	**
	480	0:50	3	41	64	93	122	142	187	654:00	**
	720	0:50	32	74	100	114	122	142	187	773:00	**
130	10								0	2:10	*
	15	2:00							1	3:10	F
	20	2:00							4	6:10	H
	25	2:00							10	12:10	J
	30	1:50						3	18	23:10	M
	40	1:50						10	25	37:10	N
	50	1:40					3	21	37	63:10	O
	60	1:40					9	23	52	86:10	Z
	70	1:40					16	24	61	103:10	Z
	80	1:30				3	19	35	72	131:10	Z
	90	1:30				8	19	45	80	154:10	Z

	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet) 90	80	70	60	50	40	30	20	10	Total decompression time (min:sec)	Repeti-tive group
140	10										0	2:20	*
	15	2:10									2	4:20	G
	20	2:10									6	8:20	I
	25	2:00								2	14	18:20	J
	30	2:00								5	21	28:20	K
	40	1:50							2	16	26	46:20	N
	50	1:50							6	24	44	76:20	O
	60	1:50							16	23	56	97:20	Z
	70	1:40						4	19	32	68	125:20	Z
	80	1:40						10	23	41	79	155:20	Z
	90	1:30					2	14	18	42	88	166:20	**
	120	1:30					12	14	36	56	120	240:20	**
	180	1:20				10	26	32	54	94	168	386:20	**
	240	1:10			8	28	34	50	78	124	187	511:20	**
	360	1:00		9	32	42	64	84	122	142	187	684:20	**
	480	1:00		31	44	59	100	114	122	142	187	801:20	**
	720	0:50	16	56	88	97	100	114	122	142	187	924:20	**

***See No Decompression Table for repetitive groups**
****Repetitive dives may not follow exceptional exposure dives**

Source: U.S. Navy (1988)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet)									Total decompression time (min:sec)	Repetitive group
			90	80	70	60	50	40	30	20	10		
150	5										0	2:30	C
	10	2:20									1	3:30	E
	15	2:20									3	5:30	G
	20	2:10								2	7	11:30	H
	25	2:10								4	17	23:30	K
	30	2:10								8	24	34:30	L
	40	2:00							5	19	33	59:30	N
	50	2:00							12	23	51	88:30	O
	60	1:50						3	19	26	62	112:30	Z
	70	1:50						11	19	39	75	146:30	Z
	80	1:40					1	17	19	50	84	173:30	Z
160	5										0	2:40	D
	10	2:30									1	3:40	F
	15	2:20								1	4	7:40	H
	20	2:20								3	11	16:40	J
	25	2:20								7	20	29:40	K
	30	2:10							2	11	25	40:40	M
	40	2:10							7	23	39	71:40	N
	50	2:00						2	16	23	55	98:40	Z
	60	2:00						9	19	33	69	132:40	Z
	70	1:50					1	17	22	44	80	166:40	**

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet)											Total decompression time (min:sec)	Repetitive group
			110	100	90	80	70	60	50	40	30	20	10		
170	5												0	2:50	D
	10	2:40											2	4:50	F
	15	2:30										2	5	9:50	H
	20	2:30										4	15	21:50	J
	25	2:20									2	7	23	34:50	L
	30	2:20									4	13	26	45:50	M
	40	2:10								1	10	23	45	81:50	O
	50	2:10								5	18	23	61	109:50	Z
	60	2:00							2	15	22	37	74	152:50	Z
	70	2:00							8	17	19	51	86	183:50	**
	90	1:50						12	12	14	34	52	120	246:50	**
	120	1:30				2	10	12	18	32	42	82	156	356:50	**
	180	1:20			4	10	22	28	34	50	78	120	187	535:50	**
	240	1:20			18	24	30	42	50	70	116	142	187	681:50	**
	360	1:10		22	34	40	52	60	98	114	122	142	187	873:50	**
	480	1:00	14	40	42	56	91	97	100	114	122	142	187	1007:50	**
180	5												0	3:00	D
	10	2:50											3	6:00	F
	15	2:40										3	6	12:00	I
	20	2:30									1	5	17	26:00	K
	25	2:30									3	10	24	40:00	L
	30	2:30									6	17	27	53:00	N
	40	2:20								3	14	23	50	93:00	O
	50	2:10							2	9	19	30	65	128:00	Z
	60	2:10							5	16	19	44	81	168:00	Z

*See No Decompression Table for repetitive groups

**Repetitive dives may not follow exceptional exposure dives

Source: U.S. Navy (1988)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet)											Total decompression time (min:sec)	Repetitive group
			110	100	90	80	70	60	50	40	30	20	10		
190	5	2:50											0	3:10	D
	10	2:50										1	3	7:10	G
	15	2:50										4	7	14:10	I
	20	2:40									2	6	20	31:10	K
	25	2:40									5	11	25	44:10	M
	30	2:30								1	8	19	32	63:10	N
	40	2:30								8	14	23	55	103:10	O
	50	2:20							4	13	22	33	72	147:10	**
	60	2:20							10	17	19	50	84	183:10	**

	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet)													Total decompression time (min:sec)
			130	120	110	100	90	80	70	60	50	40	30	20	10	
200	5	3:10													1	4:20
	10	3:00												1	4	8:20
	15	2:50											1	4	10	18:20
	20	2:50											3	7	27	40:20
	25	2:50											7	14	25	49:20
	30	2:40										2	9	22	37	73:20
	40	2:30									2	8	17	23	59	112:20
	50	2:30									6	16	22	39	75	161:20
	60	2:20								2	13	17	24	51	89	199:20
	90	1:50					1	10	10	12	12	30	38	74	134	324:20
	120	1:40				6	10	10	10	24	28	40	64	98	180	473:20
	180	1:20		1	10	10	18	24	24	42	48	70	106	142	187	685:20
	240	1:20		6	20	24	24	36	42	54	68	114	122	142	187	842:20
	360	1:10	12	22	36	40	44	56	82	98	100	114	122	142	187	1058:20
210	5	3:20													1	4:30
	10	3:10												2	4	9:30
	15	3:00											1	5	13	22:30
	20	3:00											4	10	23	40:30
	25	2:50										2	7	17	27	56:30
	30	2:50										4	9	24	41	81:30
	40	2:40									4	9	19	26	63	124:30
	50	2:30								1	9	17	19	45	80	174:30
220	5	3:30													1	5:40
	10	3:20												2	5	10:40
	15	3:10											2	5	16	26:40
	20	3:00										1	3	11	24	42:40
	25	3:00										3	8	19	33	66:40
	30	2:50									1	7	10	23	47	91:40
	40	2:50									6	12	22	29	68	140:40
	50	2:40								3	12	17	18	51	86	190:40

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*See No Decompression Table for repetitive groups

**Repetitive dives may not follow exceptional exposure dives

Source: U.S. Navy (1988)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet)													Total decompression time (min:sec)
			130	120	110	100	90	80	70	60	50	40	30	20	10	
230	5	3:40													2	5:50
	10	3:20											1	2	6	12:50
	15	3:20											3	6	18	30:50
	20	3:10										2	5	12	26	48:50
	25	3:10										4	8	22	37	74:50
	30	3:00									2	8	12	23	51	99:50
	40	2:50								1	7	15	22	34	74	156:50
	50	2:50								5	14	16	24	51	89	202:50
240	5	3:50													2	6:00
	10	3:30											1	3	6	14:00
	15	3:30											4	6	21	35:00
	20	3:20										3	6	15	25	53:00
	25	3:10									1	4	9	24	40	82:00
	30	3:10									4	8	15	22	56	109:00
	40	3:00								3	7	17	22	39	75	167:00
	50	2:50							1	8	15	16	29	51	94	218:00

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet)																				Total decompression time (min:sec)
			200	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	40	30	20	10	
250	5	3:50																			1	2	7:10
	10	3:40																		1	4	7	16:10
	15	3:30																	1	4	7	22	38:10
	20	3:30																	4	7	17	27	59:10
	25	3:20																2	7	10	24	45	92:10
	30	3:20																6	7	17	23	59	116:10
	40	3:10															5	9	17	19	45	79	178:10
	60	2:40												4	10	10	10	12	22	36	64	164	298:10
	90	2:10									8	10	10	10	10	10	28	28	44	68	98	186	514:10
	120	1:50							5	10	10	10	10	16	24	24	36	48	64	94	142	187	684:10
	180	1:30					4	8	8	10	22	24	24	32	42	44	60	84	114	122	142	187	931:10
	240	1:30					9	14	21	22	22	40	40	42	56	76	98	100	114	122	142	187	1109:10
260	5	4:00																			1	2	7:20
	10	3:50																		2	4	9	19:20
	15	3:40																	2	4	10	22	42:20
	20	3:30																1	4	7	20	31	67:20
	25	3:30																3	8	11	23	50	99:20
	30	3:20															2	6	8	19	26	61	126:20
	40	3:10														1	6	11	16	19	49	84	190:20
270	5	4:10																			1	3	8:30
	10	4:00																		2	5	11	22:30
	15	3:50																	3	4	11	24	46:30
	20	3:40																2	3	9	21	35	74:30
	25	3:30															2	3	8	13	23	53	106:30
	30	3:30															3	6	12	22	27	64	138:30
	40	3:20														5	6	11	17	22	51	88	204:30

Source: U.S. Navy (1988)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Decompression stops (feet) 200	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	40	30	20	10	Total decompression time (min:sec)
280	5	4:20																			2	2	8:40
	10	4:00																	1	2	5	13	25:40
	15	3:50																1	3	4	11	26	49:40
	20	3:50																3	4	8	23	39	81:40
	25	3:40															2	5	7	16	23	56	113:40
	30	3:30														1	3	7	13	22	30	70	150:40
	40	3:20													1	6	6	13	17	27	51	93	218:40
290	5	4:30																			2	3	9:50
	10	4:10																	1	3	5	16	29:50
	15	4:00																1	3	6	12	26	52:50
	20	4:00																3	7	9	23	43	89:50
	25	3:50															3	5	8	17	23	60	120:50
	30	3:40														1	5	6	16	22	36	72	162:50
	40	3:30													3	5	7	15	16	32	51	95	228:50
300	5	4:40																			3	3	11:00
	10	4:20																	1	3	6	17	32:00
	15	4:10																2	3	6	15	26	57:00
	20	4:00															2	3	7	10	23	47	97:00
	25	3:50														1	3	6	8	19	26	61	129:00
	30	3:50														2	5	7	17	22	39	75	172:00
	40	3:40													4	6	9	15	17	34	51	90	231:00
	60	3:00									4	10	10	10	10	10	14	28	32	50	90	187	460:00
	90	2:20					3	8	8	10	10	10	10	16	24	24	34	48	64	90	142	187	693:00
	120	2:00			4	8	8	8	8	10	14	24	24	24	34	42	58	66	102	122	142	187	890:00
	180	1:40	6	8	8	8	14	20	21	21	28	40	40	48	56	82	98	100	114	122	142	187	1168:00

Source: U.S. Navy (1988)

NO-DECOMPRESSION LIMITS AND REPETITIVE GROUP DESIGNATION TABLE FOR NO-DECOMPRESSION AIR DIVES

Depth (feet)	No-decom-pression limits (min)	Group Designation A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
10		60	120	210	300											
15		35	70	110	160	225	350									
20		25	50	75	100	135	180	240	325							
25		20	35	55	75	100	125	160	195	245	315					
30		15	30	45	60	75	95	120	145	170	205	250	310			
35	310	5	15	25	40	50	60	80	100	120	140	160	190	220	270	310
40	200	5	15	25	30	40	50	70	80	100	110	130	150	170	200	
50	100		10	15	25	30	40	50	60	70	80	90	100			
60	60		10	15	20	25	30	40	50	55	60					
70	50		5	10	15	20	30	35	40	45	50					
80	40		5	10	15	20	25	30	35	40						
90	30		5	10	12	15	20	25	30							
100	25		5	7	10	15	20	22	25							
110	20			5	10	13	15	20								
120	15			5	10	12	15									
130	10			5	8	10										
140	10			5	7	10										
150	5			5												
160	5				5											
170	5				5											
180	5				5											
190	5				5											

Source: U.S. Navy (1988)

RESIDUAL NITROGEN TIMETABLE FOR REPETITIVE AIR DIVES

Locate the diver's repetitive group designation from his previous dive along the diagonal line above the table. Read horizontally to the interval in which the diver's surface interval lies.

Next read vertically downward to the new repetitive group designation. Continue downward in this same column to the row which represents the depth of the repetitive dive. The time given at the intersection is residual nitrogen time, in minutes, to be applied to the repetitive dive.

* Dives following surface intervals of more than 12 hours are not repetitive dives. Use actual bottom times in the Standard Air Decompression Tables to compute decompression for such dives.

** If no Residual Nitrogen Time is given, then the repetitive group does not change.

Repetitive group at the beginning of the surface interval	Z	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
A																0:10 12:00*
B															0:10 2:10	2:11 12:00*
C														0:10 1:39	1:40 2:49	2:50 12:00*
D													0:10 1:09	1:10 2:38	2:39 5:48	5:49 12:00*
E												0:10 0:54	0:55 1:57	1:58 3:22	3:23 6:32	6:33 12:00*
F											0:10 0:45	0:46 1:29	1:30 2:28	2:29 3:57	3:58 7:05	7:06 12:00*
G										0:10 0:40	0:41 1:15	1:16 1:59	2:00 2:58	2:59 4:25	4:26 7:35	7:36 12:00*
H									0:10 0:36	0:37 1:06	1:07 1:41	1:42 2:23	2:24 3:20	3:21 4:49	4:50 7:59	8:00 12:00*
I								0:10 0:33	0:34 0:59	1:00 1:29	1:30 2:02	2:03 2:44	2:45 3:43	3:44 5:12	5:13 8:21	8:22 12:00*
J							0:10 0:31	0:32 0:54	0:55 1:19	1:20 1:47	1:48 2:20	2:21 3:04	3:05 4:02	4:03 5:40	5:41 8:40	8:41 12:00*
K						0:10 0:28	0:29 0:49	0:50 1:11	1:12 1:35	1:36 2:03	2:04 2:38	2:39 3:21	3:22 4:19	4:20 5:48	5:49 8:58	8:59 12:00*
L					0:10 0:26	0:27 0:45	0:46 1:04	1:05 1:25	1:26 1:49	1:50 2:19	2:20 2:53	2:54 3:36	3:37 4:35	4:36 6:02	6:03 9:12	9:13 12:00*
M				0:10 0:25	0:26 0:42	0:43 0:59	1:00 1:18	1:19 1:39	1:40 2:05	2:06 2:34	2:35 3:08	3:09 3:52	3:53 4:49	4:50 6:18	6:19 9:28	9:29 12:00*
N			0:10 0:24	0:25 0:39	0:40 0:54	0:55 1:11	1:12 1:30	1:31 1:53	1:54 2:18	2:19 2:47	2:48 3:22	3:23 4:04	4:05 5:03	5:04 6:32	6:33 9:43	9:44 12:00*
O		0:10 0:23	0:24 0:36	0:37 0:51	0:52 1:07	1:08 1:24	1:25 1:43	1:44 2:04	2:05 2:29	2:30 2:59	3:00 3:33	3:34 4:17	4:18 5:16	5:17 6:44	6:45 9:54	9:55 12:00*
Z	0:10 0:22	0:23 0:34	0:35 0:48	0:49 1:02	1:03 1:18	1:19 1:36	1:37 1:55	1:56 2:17	2:18 2:42	2:43 3:10	3:11 3:45	3:46 4:29	4:30 5:27	5:28 6:56	6:57 10:05	10:06 12:00*

NEW GROUP DESIGNATION

REPETITIVE DIVE DEPTH	Z	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
10	**	**	**	**	**	**	**	**	**	**	**	**	279	159	88	39
20	**	**	**	**	**	**	**	399	279	208	159	120	88	62	39	18
30	**	**	469	349	279	229	190	159	132	109	88	70	54	39	25	12
40	257	241	213	187	161	138	116	101	87	73	61	49	37	25	17	7
50	169	160	142	124	111	99	87	76	66	56	47	38	29	21	13	6
60	122	117	107	97	88	79	70	61	52	44	36	30	24	17	11	5
70	100	96	87	80	72	64	57	50	43	37	31	26	20	15	9	4
80	84	80	73	68	61	54	48	43	38	32	28	23	18	13	8	4
90	73	70	64	58	53	47	43	38	33	29	24	20	16	11	7	3
100	64	62	57	52	48	43	38	34	30	26	22	18	14	10	7	3
110	57	55	51	47	42	38	34	31	27	24	20	16	13	10	6	3
120	52	50	46	43	39	35	32	28	25	21	18	15	12	9	6	3
130	46	44	40	38	35	31	28	25	22	19	16	13	11	8	6	3
140	42	40	38	35	32	29	26	23	20	18	15	12	10	7	5	2
150	40	38	35	32	30	27	24	22	19	17	14	12	9	7	5	2
160	37	36	33	31	28	26	23	20	18	16	13	11	9	6	4	2
170	35	34	31	29	26	24	22	19	17	15	13	10	8	6	4	2
180	32	31	29	27	25	22	20	18	16	14	12	10	8	6	4	2
190	31	30	28	26	24	21	19	17	15	13	11	10	8	6	4	2

RESIDUAL NITROGEN TIMES (MINUTES)

Source: U.S. Navy (1988)

SURFACE DECOMPRESSION TABLE USING OXYGEN

Depth (feet)	Bottom time (min)	Time to first stop or surface (min:sec)	Time (min) breathing air at water stops (ft)				Surface interval	Time at 40-foot chamber stop (min) on oxygen	Surface	Total decompression time (min:sec)
			60	50	40	30				
70	52	2:48	0	0	0	0	TOTAL TIME FROM LAST WATER STOP TO FIRST CHAMBER STOP NOT TO EXCEED 5 MINUTES	0	2-MINUTE ASCENT FROM 40 FEET IN CHAMBER TO SURFACE WHILE BREATHING OXYGEN	2:48
	90	2:48	0	0	0	0		15		23:48
	120	2:48	0	0	0	0		23		31:48
	150	2:48	0	0	0	0		31		39:48
	180	2:48	0	0	0	0		39		47:48
80	40	3:12	0	0	0	0		0		3:12
	70	3:12	0	0	0	0		14		23:12
	85	3:12	0	0	0	0		20		29:12
	100	3:12	0	0	0	0		26		35:12
	115	3:12	0	0	0	0		31		40:12
	130	3:12	0	0	0	0		37		46:12
	150	3:12	0	0	0	0		44		53:12
90	32	3:36	0	0	0	0		0		3:36
	60	3:36	0	0	0	0		14		23:36
	70	3:36	0	0	0	0		20		29:36
	80	3:36	0	0	0	0		25		34:36
	90	3:36	0	0	0	0		30		39:36
	100	3:36	0	0	0	0		34		43:36
	110	3:36	0	0	0	0		39		48:36
	120	3:36	0	0	0	0		43		52:36
	130	3:36	0	0	0	0		48		57:36
100	26	4:00	0	0	0	0		0		4:00
	50	4:00	0	0	0	0		14		24:00
	60	4:00	0	0	0	0		20		30:00
	70	4:00	0	0	0	0		26		36:00
	80	4:00	0	0	0	0		32		42:00
	90	4:00	0	0	0	0		38		48:00
	100	4:00	0	0	0	0		44		54:00
	110	4:00	0	0	0	0		49		59:00
	120	2:48	0	0	0	3		53		65:48
110	22	4:24	0	0	0	0		0		4:24
	40	4:24	0	0	0	0		12		22:24
	50	4:24	0	0	0	0		19		29:24
	60	4:24	0	0	0	0		26		36:24
	70	4:24	0	0	0	0		33		43:24
	80	3:12	0	0	0	1		40		51:12
	90	3:12	0	0	0	2		46		58:12
	100	3:12	0	0	0	5		51		66:12
	110	3:12	0	0	0	12		54		76:12
120	18	4:48	0	0	0	0		0		4:48
	30	4:48	0	0	0	0		9		19:48
	40	4:48	0	0	0	0		16		26:48
	50	4:48	0	0	0	0		24		34:48
	60	3:36	0	0	0	2		32		44:36
	70	3:36	0	0	0	4		39		53:36
	80	3:36	0	0	0	5		46		61:36
	90	3:12	0	0	3	7		51		72:12
	100	3:12	0	0	6	15		54		86:12

Source: U.S. Navy (1988)

SURFACE DECOMPRESSION TABLE USING OXYGEN

Depth (feet)	Bottom time (min)	Time to first stop or surface (min:sec)	Time (min) breathing air at water stops (ft)				Surface interval	Time at 40-foot chamber stop (min) on oxygen	Surface	Total decompression time (min:sec)
			60	50	40	30				
130	15	5:12	0	0	0	0	TOTAL TIME FROM LAST WATER STOP TO FIRST CHAMBER STOP NOT TO EXCEED 5 MINUTES	0	2-MINUTE ASCENT FROM 40 FEET IN CHAMBER TO SURFACE WHILE BREATHING OXYGEN	5:12
	30	5:12	0	0	0	0		12		23:12
	40	5:12	0	0	0	0		21		32:12
	50	4:00	0	0	0	3		29		43:00
	60	4:00	0	0	0	5		37		53:00
	70	4:00	0	0	0	7		45		63:00
	80	3:36	0	0	6	7		51		75:36
	90	3:36	0	0	10	12		56		89:36
140	13	5:36	0	0	0	0		0		5:36
	25	5:36	0	0	0	0		11		22:36
	30	5:36	0	0	0	0		15		26:36
	35	5:36	0	0	0	0		20		31:36
	40	4:24	0	0	0	2		24		37:24
	45	4:24	0	0	0	4		29		44:24
	50	4:24	0	0	0	6		33		50:24
	55	4:24	0	0	0	7		38		56:24
	60	4:24	0	0	0	8		43		62:24
	65	4:00	0	0	3	7		48		70:00
	70	3:36	0	2	7	7		51		79:36
150	11	6:00	0	0	0	0		0		6:00
	25	6:00	0	0	0	0		13		25:00
	30	6:00	0	0	0	0		18		30:00
	35	4:48	0	0	0	4		23		38:48
	40	4:24	0	0	3	6		27		48:24
	45	4:24	0	0	5	7		33		57:24
	50	4:00	0	2	5	8		38		66:00
	55	3:36	2	5	9	4		44		77:36
160	9	6:24	0	0	0	0		0		6:24
	20	6:24	0	0	0	0		11		23:24
	25	6:24	0	0	0	0		16		28:24
	30	5:12	0	0	0	2		21		35:12
	35	4:48	0	0	4	6		26		48:48
	40	4:24	0	3	5	8		32		61:24
	45	4:00	3	4	8	6		38		73:00
170	7	6:48	0	0	0	0		0		6:48
	20	6:48	0	0	0	0		13		25:48
	25	6:48	0	0	0	0		19		31:48
	30	5:12	0	0	3	5		23		44:12
	35	4:48	0	4	4	7		29		57:48
	40	4:24	4	4	8	6		36		72:24

Source: U.S. Navy (1988)

SURFACE DECOMPRESSION TABLE USING AIR

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Time at water stops (min)			Surface Interval	Chamber stops (air) (min)		Total decompression time (min:sec)
			30	20	10		20	10	
40	230	0:30			3	TOTAL TIME FROM LAST WATER STOP TO FIRST CHAMBER STOP NOT TO EXCEED 5 MINUTES		7	14:30
	250	0:30			3			11	18:30
	270	0:30			3			15	22:30
	300	0:30			3			19	26:30
50	120	0:40			3			5	12:40
	140	0:40			3			10	17:40
	160	0:40			3			21	28:40
	180	0:40			3			29	36:40
	200	0:40			3			35	42:40
	220	0:40			3			40	47:40
	240	0:40			3			47	54:40
60	80	0:50			3			7	14:50
	100	0:50			3			14	21:50
	120	0:50			3			26	33:50
	140	0:50			3			39	46:50
	160	0:50			3			48	55:50
	180	0:50			3			56	63:50
	200	0:40		3			3	69	80:10
70	60	1:00			3			8	16:00
	70	1:00			3			14	22:00
	80	1:00			3			18	26:00
	90	1:00			3			23	31:00
	100	1:00			3			33	41:00
	110	0:50		3			3	41	52:20
	120	0:50		3			4	47	59:20
	130	0:50		3			6	52	66:20
	140	0:50		3			8	56	72:20
	150	0:50		3			9	61	78:20
	160	0:50		3			13	72	93:20
	170	0:50		3			19	79	106:20
80	50	1:10			3			10	18:10
	60	1:10			3			17	25:10
	70	1:10			3			23	31:10
	80	1:00		3			3	31	42:30
	90	1:00		3			7	39	54:30
	100	1:00		3			11	46	65:30
	110	1:00		3			13	53	74:30
	120	1:00		3			17	56	81:30
	130	1:00		3			19	63	90:30
	140	1:00		26			26	69	126:30
	150	1:00		32			32	77	146:30
90	40	1:20			3			7	15:20
	50	1:20			3			18	26:20
	60	1:20			3			25	33:20
	70	1:10		3			7	30	45:40
	80	1:10		13			13	40	71:40
	90	1:10		18			18	48	89:40
	100	1:10		21			21	54	101:40
	110	1:10		24			24	61	114:40
	120	1:10		32			32	68	137:40
	130	1:00	5	36			36	74	156:40
100	40	1:30			3			15	23:30
	50	1:20		3			3	24	35:50
	60	1:20		3			9	28	45:50
	70	1:20		3			17	39	64:50
	80	1:20		23			23	48	99:50
	90	1:10	3	23			23	57	111:50
	100	1:10	7	23			23	66	124:50
	110	1:10	10	34			34	72	155:50
	120	1:10	12	41			41	78	177:50
110	30	1:40			3			7	15:40
	40	1:30		3			3	21	33:00
	50	1:30		3			8	26	43:00
	60	1:30		18			18	36	78:00
	70	1:20	1	23			23	48	101:00
	80	1:20	7	23			23	57	116:00
	90	1:20	12	30			30	64	142:00
	100	1:20	15	37			37	72	167:00

Source: U.S. Navy (1988)

SURFACE DECOMPRESSION TABLE USING AIR

Depth (feet)	Bottom time (min)	Time to first stop (min:sec)	Time at water stops (min)					Surface interval	Chamber stops (air) (min)		Total decompression time (min:sec)
			50	40	30	20	10		20	10	
120	25	1:50					3			6	14:50
	30	1:50					3			14	22:50
	40	1:40				3			5	25	39:10
	50	1:40				15			15	31	67:10
	60	1:30			2	22			22	45	97:10
	70	1:30			9	23			23	55	116:10
	80	1:30			15	27			27	63	138:10
	90	1:30			19	37			37	74	173:10
	100	1:30			23	45			45	80	189:10
130	25	2:00					3			10	19:00
	30	1:50				3		TOTAL TIME FROM LAST WATER STOP TO FIRST CHAMBER STOP NOT TO EXCEED 5 MINUTES	3	18	30:20
	40	1:50				10			10	25	51:20
	50	1:40			3	21			21	37	88:20
	60	1:40			9	23			23	52	113:20
	70	1:40			16	24			24	61	131:20
	80	1:30		3	19	35			35	72	170:20
	90	1:30		8	19	45			45	80	203:20
140	20	2:10					3			6	15:10
	25	2:00				3			3	14	26:30
	30	2:00				5			5	21	37:30
	40	1:50			2	16			16	26	66:30
	50	1:50			6	24			24	44	104:30
	60	1:50			16	23			23	56	124:30
	70	1:40		4	19	32			32	68	161:30
	80	1:40		10	23	41			41	79	200:30
150	20	2:10				3			3	7	19:40
	25	2:10				4			4	17	31:40
	30	2:10				8			8	24	46:40
	40	2:00			5	19			19	33	82:40
	50	2:00			12	23			23	51	115:40
	60	1:50		3	19	26			26	62	142:40
	70	1:50		11	19	39			39	75	189:40
	80	1:40	1	17	19	50			50	84	227:40
160	20	2:20				3			3	11	23:50
	25	2:20				7			7	20	40:50
	30	2:10			2	11			11	25	55:50
	40	2:10			7	23			23	39	98:50
	50	2:00		2	16	23			23	55	125:50
	60	2:00		9	19	33			33	69	169:50
	70	1:50	1	17	22	44			44	80	214:50
170	15	2:30				3			3	5	18:00
	20	2:30				4			4	15	30:00
	25	2:20			2	7			7	23	46:00
	30	2:20			4	13			13	26	63:00
	40	2:10		1	10	23			23	45	109:00
	50	2:10		5	18	23			23	61	137:00
	60	2:00	2	15	22	37			37	74	194:00
	70	2:00	8	17	19	51			51	86	239:00
180	15	2:40				3			3	6	19:10
	20	2:30			1	5			5	17	35:10
	25	2:30			3	10			10	24	54:10
	30	2:30			6	17			17	27	74:10
	40	2:20		3	14	23			23	50	120:10
	50	2:10	2	9	19	30			30	65	162:10
	60	2:10	5	16	19	44			44	81	216:10
190	15	2:50				4			4	7	22:20
	20	2:40			2	6			6	20	41:20
	25	2:40			5	11			11	25	59:20
	30	2:30		1	8	19			19	32	86:20
	40	2:30		8	14	23			23	55	130:20
	50	2:20	4	13	22	33			33	72	184:20
	60	2:20	10	17	19	50			50	84	237:20

Source: U.S. Navy (1988)

APPENDIX C
TREATMENT FLOWCHART AND RECOMPRESSION TREATMENT TABLES

APPENDIX C
TREATMENT FLOWCHART AND RECOMPRESSION TREATMENT TABLES

INTRODUCTION

This appendix contains a Diving Accident Treatment Flowchart and a number of treatment tables used to recompress divers who have experienced decompression sickness or arterial gas embolism as a result of their diving activities. The information in this appendix reflects treatment procedures recommended by the NOAA Diving Safety Board* and taught in the NOAA Diving Program. The tables presented here derive from many sources, including the U.S. Navy, the Royal Navy, NOAA, foreign organizations, and private companies. All of the tables in this appendix have been widely used in the field and have been shown to be safe and effective. Table C-1 lists these recompression tables and describes their application.

Diving Accident Treatment Flowchart

The flowchart shown in Figure C-1 is a decision tree designed to aid dive supervisors, diving physicians, Diving Emergency Medical Technicians, chamber operators, and other health care professionals who must decide how best to treat stricken divers. Use of the decision tree requires only that the diver's condition be observed; a medical diagnosis is not required for treatment to begin. Explanatory material to be used with the flowchart is shown on the facing page.

Recompression Treatment Tables

The recompression treatment tables recommended by the NOAA Diving Safety Board are shown on the following pages. Instructions for the use of these tables appear with each table and should be followed precisely.

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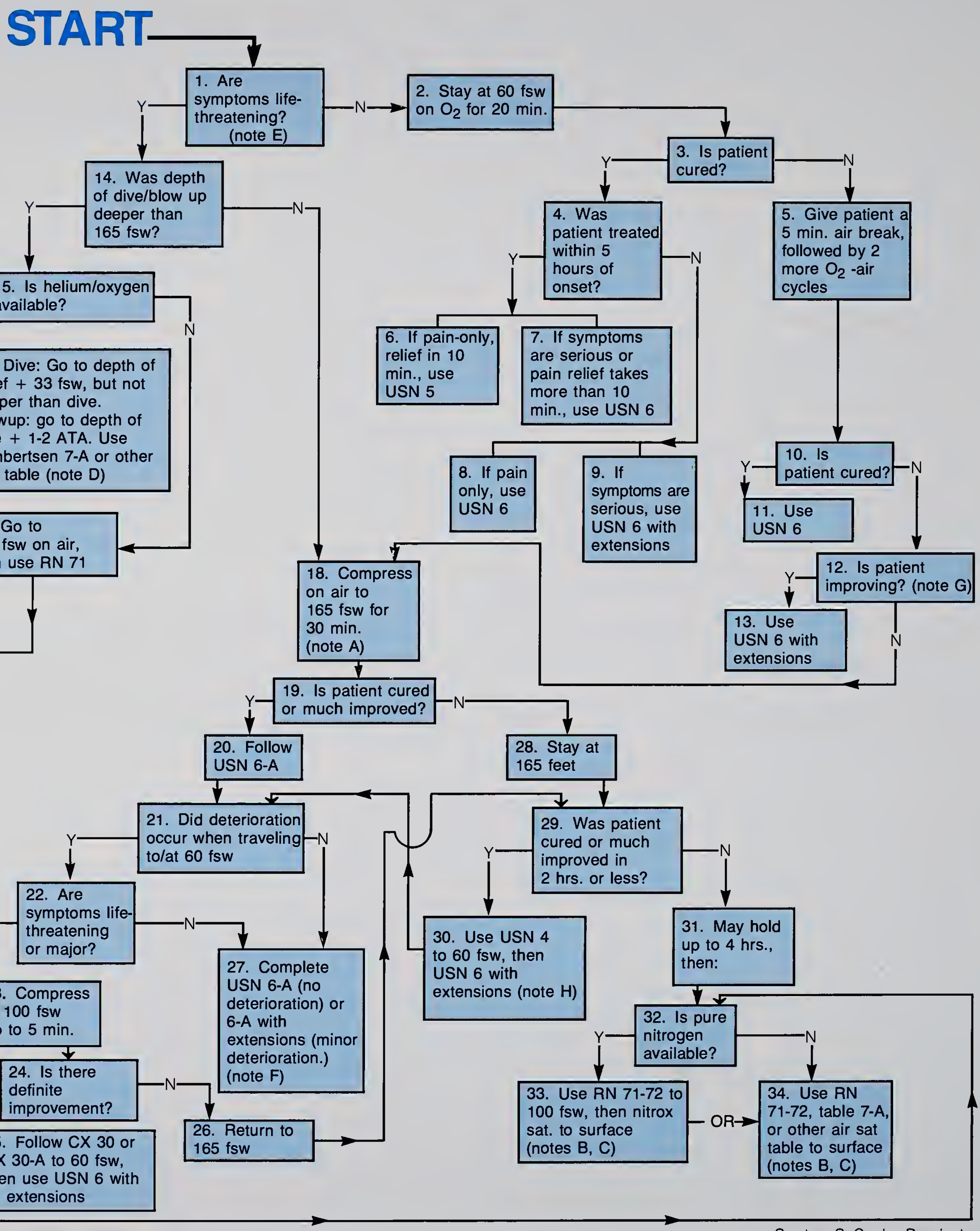
*The material in this appendix derives from C. Gordon Daugherty's *Field Guide for the Diving Medic.*

Figure C-1
Diving Accident Treatment
Flowchart



Courtesy C. Gordon Daugherty

Flowchart Comments

Flowchart
Step Number

1 - The first step is to decide if the victim's life is potentially in danger as a result of shock, convulsions, or unconsciousness. If the situation is potentially life threatening, the best immediate decision is to recompress deep. (Note that spinal symptoms, while considered serious, are not life threatening.)

2,3 - Evaluation after the first oxygen period serves to separate cases of minor bends from more serious cases.

4 - Fresh cases usually respond to standard treatment; delayed cases usually benefit from longer treatment.

5 - This step completes the 60-fsw stop on USN Table 6.

6 - This is the standard use for USN Table 5.

7 - This is the standard use for USN Table 6.

8 - In delayed cases, joint pains do not always clear completely; some mild soreness often remains. If the neurologic exam is normal, Table 6 is probably adequate.

9 - This is probably the minimum treatment for a delayed case with serious symptoms.

10 - End of the 60-fsw stop on Table 6; this is a good time to estimate the probability of the table's success.

11 - This is the appropriate treatment for a diver who is cured at this point.

12 - The question here concerns the improving diver versus the diver showing no improvement. Where there is no improvement, there is a question whether more depth will offer benefit, but this cannot be answered in advance. Long-delayed cases have a poor cure rate with any treatment. Many authorities prefer aggressive use of oxygen at 60 and 30 fsw, even on a daily basis. Assuming that a saturation treatment can be managed, it is probably advisable to go deeper.

13 - Depending on the original problem and the degree of improvement, the table can be extended at 60 fsw, 30 fsw, or both. A diver who is improving at 60 fsw usually continues to improve at 30 fsw. All other factors being equal, the more oxygen the better.

14 - In a diver with a life-threatening symptom, the first decision is how deep to go; going down to 165 fsw allows the standard tables to be used for treatment; going deeper will probably require the use of a saturation table.

15 - If the depth is deeper than 165 fsw, both heliox and chambers that are rated for the necessary depth are generally available.

16 - For a bends case, it is usually not necessary to go deeper than the dive, and the depth of relief is often shallower. Adding 33 fsw (1 atmosphere) to the depth of relief provides a margin of safety. In a blowup, bubbles may continue to form, even at the depth of the dive. Therefore, blowup cases should be compressed to the depth of the dive plus 1 or 2 ATA.

17 - If helium/oxygen is not available but the depth of the dive was greater than 165 fsw, the dive was probably a deep air dive with a short bottom time. Royal Navy Table 71 goes to 230 fsw; it can be followed in its entirety or be followed only to 60 fsw and then be replaced by USN Table 6.

18 - Cases at this step involve (1) a life-threatening accident at a depth less than 165 fsw (an embolism, for example) or (2) a serious bends case that shows no improvement after the 60-fsw stop on USN Table 6.

19 - As the treatment approaches the 30-minute bottom time on USN Table 6A, the diver's response to depth must be evaluated.

20 - This is the standard use of USN Table 6A.

21 - Deterioration while traveling to 60 fsw is a common dilemma in embolism cases.

22 - Significant deterioration requires further steps; a minor amount of deterioration can be tolerated because it will resolve as treatment continues.

23 - If deterioration is significant, it may not be necessary to return all the way to 165 fsw.

24 - Evaluate the diver after a short time at 100 fsw.

25 - If 100 fsw is sufficient, one of the Comex tables can be followed for the entire course of treatment or one of these tables can be followed to 60 fsw, after which USN Table 6 is followed.

26 - If there is no improvement at 100 fsw, the only choice is to return to 165 fsw.

27 - If there is no deterioration, this is the standard use of USN Table 6A. If there is minor deterioration, the extensions should be used.

28 - At this step, the diver's condition may either be unchanged or be improving after 30 minutes at 165 fsw.

29 - At this step, it will be possible to see either that the diver did not improve adequately after 30 minutes at 165 fsw or that the diver deteriorated during travel to 60 fsw and it was therefore necessary to return to 165 fsw. A bottom time of 2 hours or less at 165 fsw will still allow decompression to be conducted with standard tables.

30 - Table 4 will allow safe travel to 60 fsw, where USN Table 6 is substituted (with extensions). Deterioration in the diver's condition is unlikely, but this table is likely to bend the tender, who should be put on oxygen, along with the diver, at 60 fsw.

31 - If a decision is made not to decompress after 2 hours, it may be possible to hold for as long as 4 hours, depending on the diver's previous oxygen exposure. Many authorities would commence saturation decompression after 2 hours.

32 - Self-explanatory.

33 - This method has been used successfully in hospital-based treatment chambers, usually with a long hold at 100 fsw. The diver's nitrogen loading necessitates a long decompression.

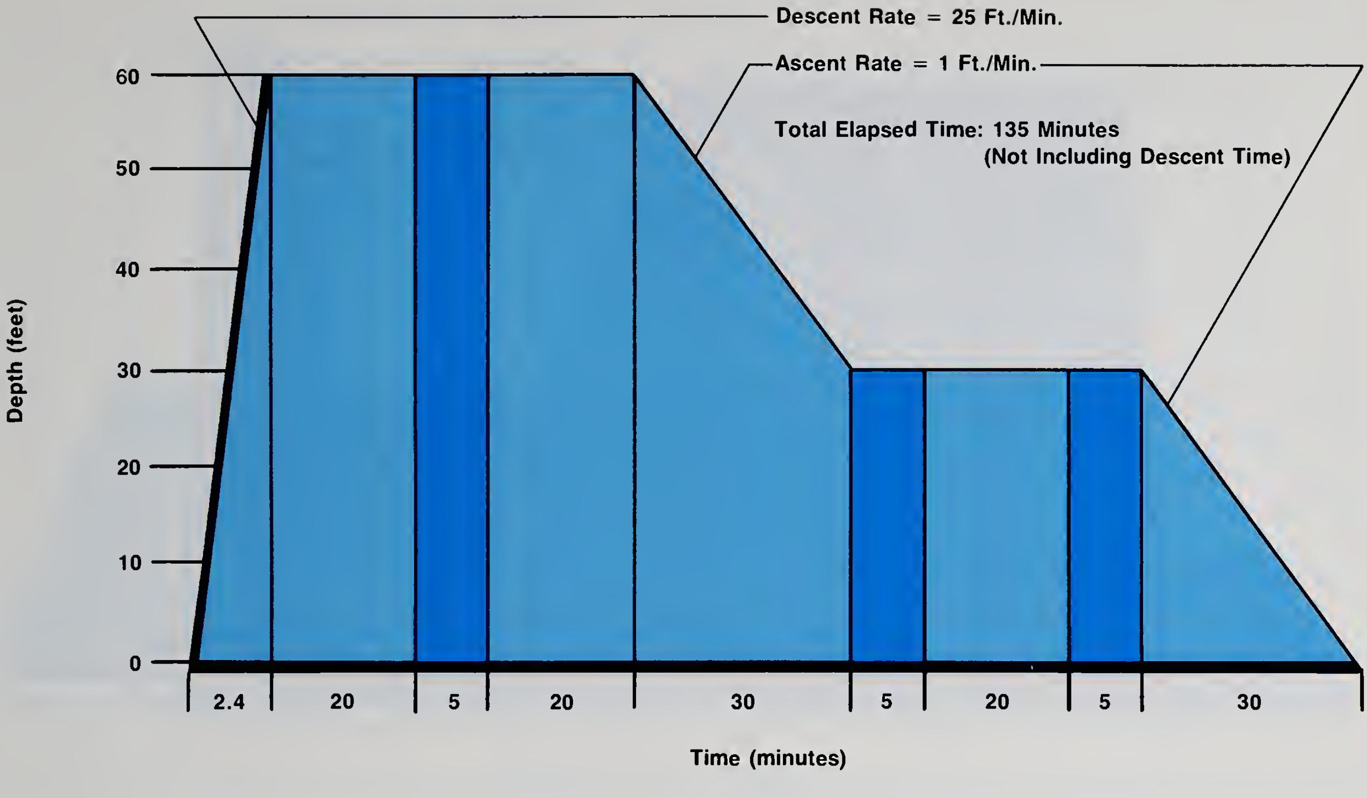
34 - An alternative approach is to continue any standard saturation decompression. Although previous oxygen exposure may prevent a hold at 100 fsw on air, very long holds (days) are possible in the range of 60-80 fsw and are limited only by symptoms of pulmonary oxygen toxicity.

Source: C. Gordon Daugherty (1983)

Table C-1
List of Recompression Tables and Their Applications

Treatment Table	Type of Table	Application
USN 5	Oxygen Treatment of Pain-Only (Type I) Decompression Sickness	Treatment of pain-only (Type I) decompression sickness in cases where symptoms are relieved within 10 minutes at a pressure (depth) of 60 fsw (18.3 msw).
USN 6	Oxygen Treatment of Serious (Type II) Decompression Sickness	Treatment of serious decompression sickness (Type II) or of pain-only (Type I) decompression sickness in cases where symptoms are NOT relieved within 10 minutes at a pressure (depth) of 60 fsw (18.3 msw).
USN 6A	Air and Oxygen Treatment of Arterial Gas Embolism	Treatment of gas embolism. This table is to be used only in cases where it is not possible to determine whether the symptoms are caused by arterial gas embolism or by serious decompression sickness.
USN 7	Oxygen/Air Treatment of Unresolved or Worsening Symptoms of Decompression Sickness or Arterial Gas Embolism	This table is to be used only in cases that are life threatening and that have not resolved after treatment on USN Table 4, 6, or 6A.
USN 1A	Air Treatment of Pain-Only (Type I) Decompression Sickness—100 fsw (30 msw) Treatment	Treatment of pain-only (Type I) decompression sickness in cases where oxygen is unavailable and the pain is relieved at a pressure (depth) shallower than 66 fsw (20 msw).
USN 2A	Air Treatment of Pain-Only (Type I) Decompression Sickness—165 fsw (50 msw)	Treatment of pain-only (Type I) decompression sickness in cases where oxygen is unavailable and pain is relieved at a pressure (depth) deeper than 66 fsw (20 msw).
USN 3	Air Treatment of Serious (Type II) Decompression Sickness or Arterial Gas Embolism	Treatment of serious (Type II) decompression sickness or arterial gas embolism in cases where oxygen is unavailable and symptoms are relieved within 30 minutes at a pressure (depth) of 165 fsw (50 msw).
USN 4	Air Treatment of Serious (Type II) Decompression Sickness or Arterial Gas Embolism	Treatment of symptoms that have worsened during the first 20-minute oxygen breathing period at a pressure (depth) of 60 fsw (18.3 msw) on Table 6, or for treatment in cases where symptoms are not relieved within 30 minutes at a pressure (depth) of 165 fsw (50 msw) when Table 3 is used.
COMEX CX 30	Helium - Oxygen or Nitrogen - Oxygen Treatment of Vestibular or Neurological (Type II) Decompression Sickness	Treatment of vestibular or serious (Type II) decompression sickness that occurs either after a normal or a shortened decompression. To be used in cases where the patient shows deterioration at a pressure (depth) of 60 fsw (18.3 msw) on USN Table 6A but shows good improvement when brought to a pressure (depth) of 100 fsw (30 msw).
COMEX CX 30A	Air Treatment of Pain-Only (Type I) Decompression Sickness When Oxygen Poisoning Has Occurred	Treatment of pain-only (Type I) decompression sickness in cases where the stricken diver shows signs of oxygen poisoning. To be used in cases where the patient shows deterioration at a pressure (depth) of 60 fsw (18.3 msw) on USN Table 6A but shows good improvement when brought to a pressure (depth) of 100 fsw (30 msw).
ROYAL NAVY 71 OR 72	Air Treatment of Decompression Sickness or Arterial Gas Embolism in Cases Where Decompression Depths Greater Than 165 fsw (50 msw) Are Needed and Mixed Gas Is Not Available	Treatment of decompression sickness or arterial gas embolism to be used in cases where patient remains in poor condition after 2 hours at a pressure (depth) of 165 fsw (50 msw) and slow decompression is desired or in cases where a pressure (depth) greater than 165 fsw (50 msw) is needed and mixed gas is not available.
LAMBERTSEN/ SOLUS OCEAN SYSTEMS TABLE 7A	Air-Oxygen Treatment Table for Symptoms of Serious Decompression Sickness That Develop Under Pressure or for Symptoms Developing at Pressure (Depths) Greater Than 165 fsw (50 msw)	Use in cases where patient develops symptoms while under pressure or where decompression sickness develops at pressures (depths) greater than 165 fsw (50 msw) or where extended recompression is necessary because symptoms have failed to resolve.
MODIFIED NOAA NITROX SATURATION TREATMENT TABLE	Nitrox Treatment Table for Serious Decompression Sickness Cases Where Treatment Was Delayed	Use in hospital chambers in severe cases of decompression sickness with delayed access to treatment.

U.S. Navy Treatment Table 5



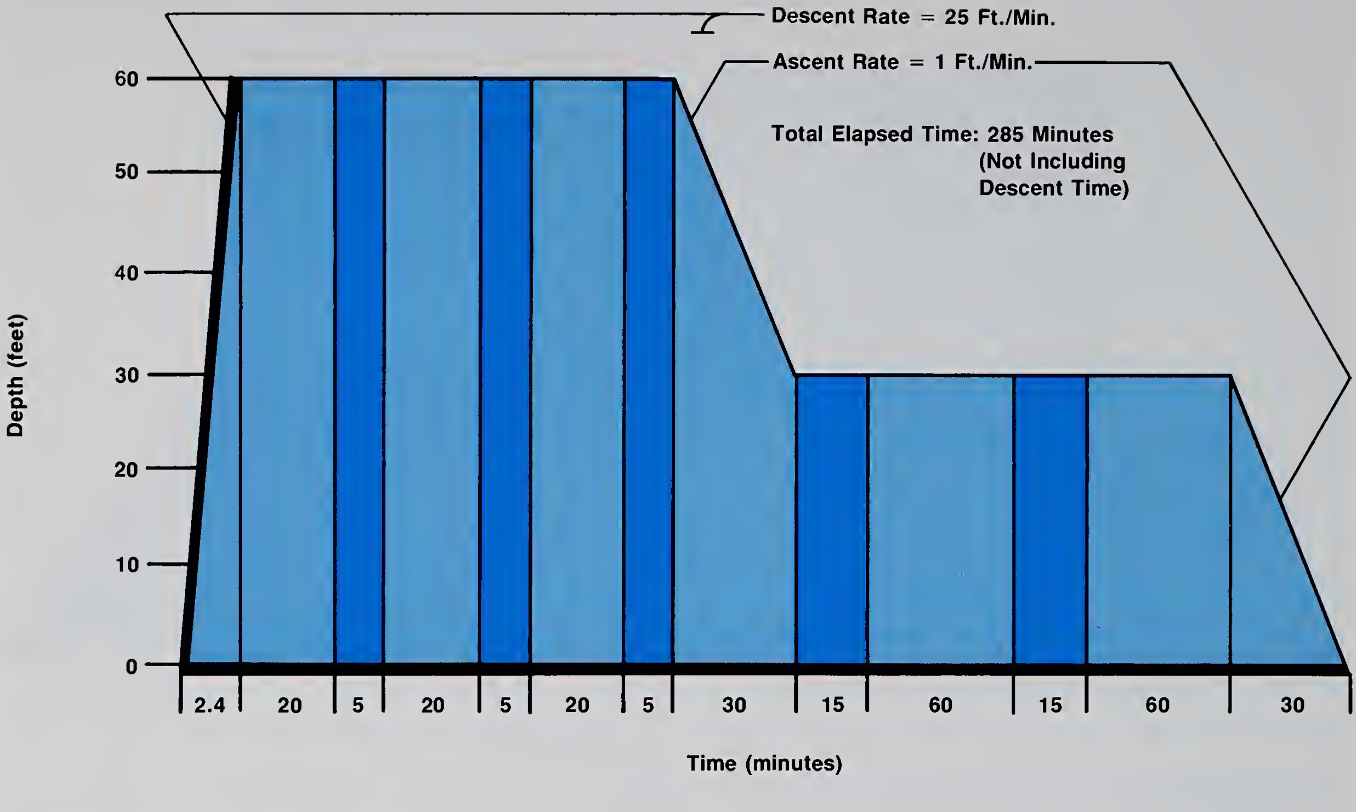
OXYGEN TREATMENT OF TYPE I DECOMPRESSION SICKNESS

1. Treatment of Type I decompression sickness when symptoms are relieved within 10 minutes at 60 feet and a complete neurological exam is normal.
2. Descent rate—25 ft/min.
3. Ascent rate—1 ft/min. Do not compensate for slower ascent rates. Compensate for faster rates by halting the ascent.
4. Time at 60 feet begins on arrival at 60 feet.
5. If oxygen breathing must be interrupted, allow 15 minutes after the reaction has entirely subsided and resume schedule at point of interruption.
6. If oxygen breathing must be interrupted at 60 feet, switch to Table 6 upon arrival at the 30 foot stop.
7. Tender breathes air throughout unless he/she has had a hyperbaric exposure within the past 12 hours, in which case he/she breathes oxygen at 30 feet.

Depth (feet)	Time (minutes)	Breathing Media	Total Elapsed Time (hrs:min.)
60	20	Oxygen	0:20
60	5	Air	0:25
60	20	Oxygen	0:45
60 to 30	30	Oxygen	1:15
30	5	Air	1:20
30	20	Oxygen	1:40
30	5	Air	1:45
30 to 0	30	Oxygen	2:15

Source: US Navy (1985)

U.S. Navy Treatment Table 6



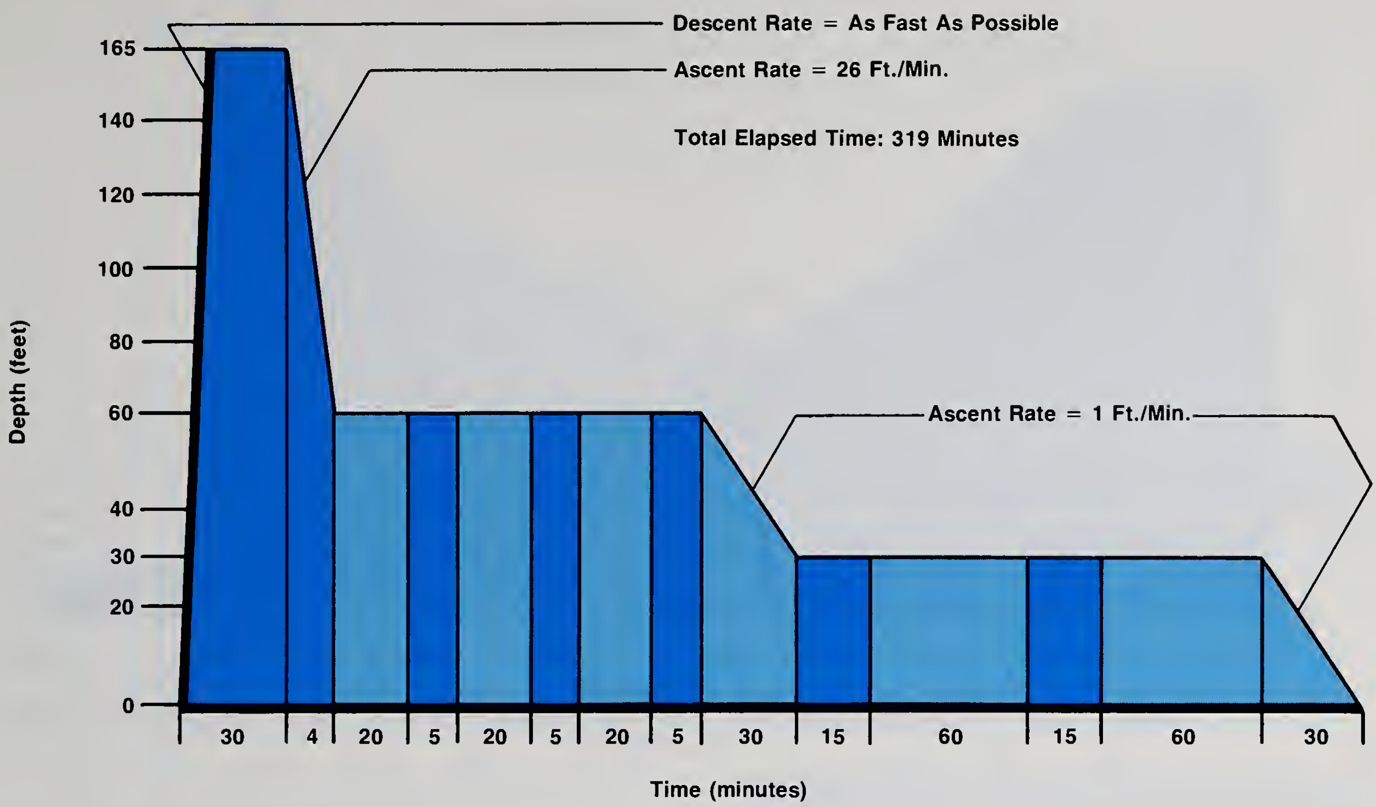
OXYGEN TREATMENT OF TYPE II DECOMPRESSION SICKNESS

1. Treatment of Type II or Type I decompression sickness when symptoms are not relieved within 10 minutes at 60 feet.
2. Descent rate—25 ft/min.
3. Ascent rate—1 ft/min. Do not compensate for slower ascent rates. Compensate for faster rates by halting the ascent.
4. Time at 60 feet begins on arrival at 60 feet.
5. If oxygen breathing must be interrupted, allow 15 minutes after the reaction has entirely subsided and resume schedule at point of interruption.
6. Tender breathes air throughout unless he/she has had a hyperbaric exposure within the past 12 hours, in which case he/she breathes oxygen at 30 feet.
7. Table 6 can be lengthened up to 2 additional 25 minute oxygen breathing periods at 60 feet (20 minutes on oxygen and 5 minutes on air) or up to 2 additional 75 minute oxygen breathing periods at 30 feet (15 minutes on air and 60 minutes on oxygen), or both. If Table 6 is extended only once at either 60 or 30 feet, the tender breathes oxygen during the ascent from 30 feet to the surface. If more than one extension is done, the tender begins oxygen breathing for the last hour at 30 feet during ascent to the surface.

Depth (feet)	Time (minutes)	Breathing Media	Total Elapsed Time (hrs:min.)
60	20	Oxygen	0:20
60	5	Air	0:25
60	20	Oxygen	0:45
60	5	Air	0:50
60	20	Oxygen	1:10
60	5	Air	1:15
60 to 30	30	Oxygen	1:45
30	15	Air	2:00
30	60	Oxygen	3:00
30	15	Air	3:15
30	60	Oxygen	4:15
30 to 0	30	Oxygen	4:45

Source: US Navy (1985)

U.S. Navy Treatment Table 6A



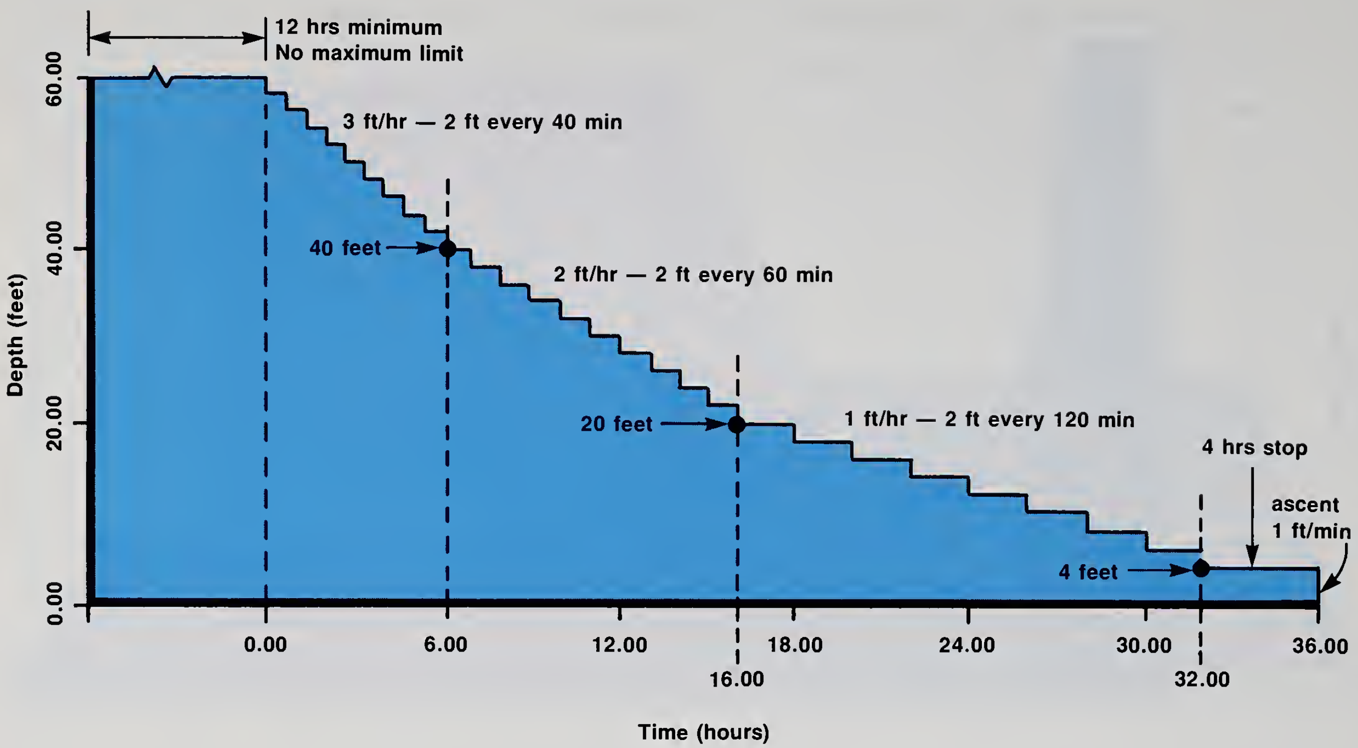
INITIAL AIR AND OXYGEN TREATMENT OF ARTERIAL GAS EMBOLISM

1. Treatment of arterial gas embolism where complete relief obtained within 30 min. at 165 feet. Use also when unable to determine whether symptoms are caused by gas embolism or severe decompression sickness.
2. Descent rate—as fast as possible.
3. Ascent rate—1 ft/min. Do not compensate for slower ascent rates. Compensate for faster ascent rates by halting the ascent.
4. Time at 165 feet—includes time from the surface.
5. If oxygen breathing must be interrupted, allow 15 minutes after the reaction has entirely subsided and resume schedule at point of interruption.
6. Tender breathes oxygen during ascent from 30 feet to the surface unless he/she has had a hyperbaric exposure within the past 12 hours, in which case he/she breathes oxygen at 30 feet.
7. Table 6A can be lengthened up to 2 additional 25 minute oxygen breathing periods at 60 feet (20 minutes on oxygen and 5 minutes on air) or up to 2 additional 75 minute oxygen breathing periods at 30 feet (15 minutes on air and 60 minutes on oxygen), or both. If Table 6A is extended either at 60 or 30 feet, the tender breathes oxygen during the last half at 30 feet and during ascent to the surface.
8. If complete relief is not obtained within 30 min. at 165 feet, switch to Table 4. Consult with a hyperbaric physician before switching if possible.

Depth (feet)	Time (minutes)	Breathing Media	Total Elapsed Time (hrs:min.)
165	30	Air	0:30
165 to 60	4	Air	0:34
60	20	Oxygen	0:54
60	5	Air	0:59
60	20	Oxygen	1:19
60	5	Air	1:29
60	20	Oxygen	1:44
60	5	Air	1:49
60 to 30	30	Oxygen	2:19
30	15	Air	2:34
30	60	Oxygen	3:34
30	15	Air	3:49
30	60	Oxygen	4:49
30 to 0	30	Oxygen	5:19

Source: US Navy (1985)

U.S. Navy Treatment Table 7

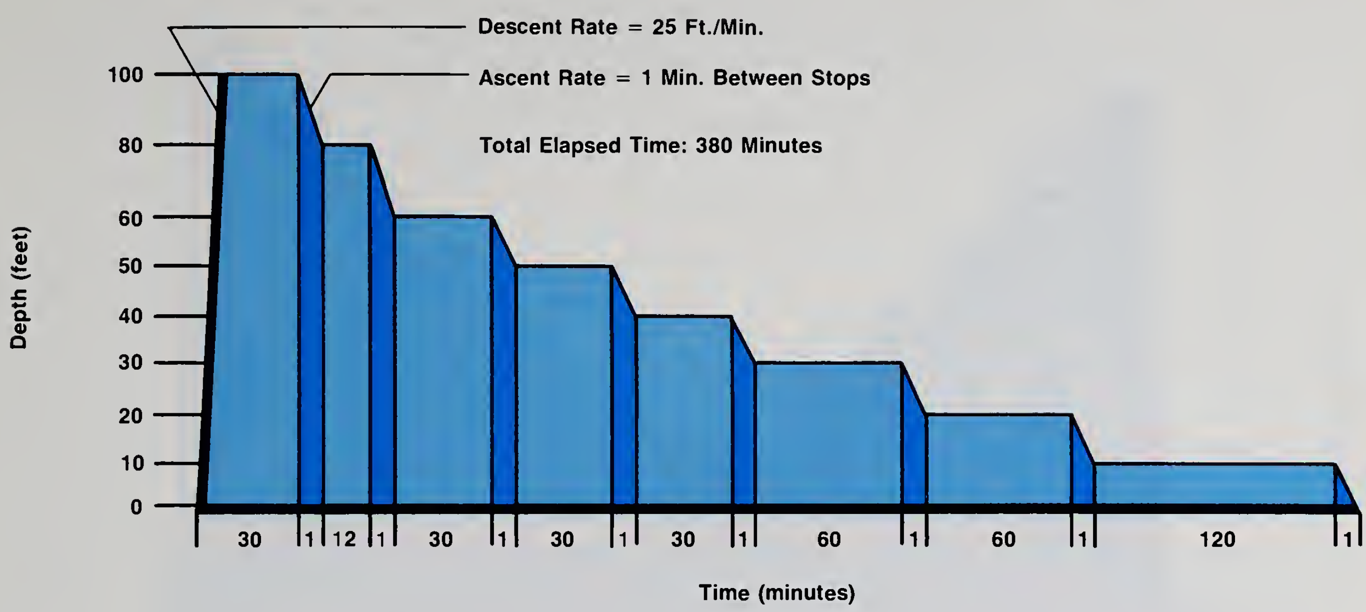


OXYGEN/AIR TREATMENT OF UNRESOLVED OR WORSENING SYMPTOMS OF DECOMPRESSION SICKNESS OR ARTERIAL GAS EMBOLISM

1. Used for treatment of unresolved life threatening symptoms after initial treatment on Table 6, 6A, or 4.
2. Use only under the direction of or in consultation with a hyperbaric physician.
3. Table begins upon arrival at 60 feet. Arrival at 60 feet accomplished by initial treatment on Table 6, 6A, or 4. If initial treatment has progressed to a depth shallower than 60 feet, compress to 60 feet at 25 ft/min to begin Table 7.
4. Maximum duration at 60 feet unlimited. Remain at 60 feet a minimum of 12 hours unless overriding circumstances dictate earlier decompression.
5. Patient begins oxygen breathing periods at 60 feet. Tender need breathe only chamber atmosphere throughout. If oxygen breathing is interrupted, no lengthening of the table is required.
6. Minimum chamber O_2 concentration 19%. Maximum CO_2 concentration 1.5% SEV (12 mmHg). Maximum chamber internal temperature 85°F.
7. Decompression starts with a 2 foot upward excursion from 60 to 58 feet. Decompress with stops every 2 feet for times shown in profile below. Ascent time between stops approximately 30 sec. Stop time begins with ascent from deeper to next shallower step. Stop at 4 feet for 4 hours and then ascend to the surface at 1 ft/min.
8. Ensure chamber life support requirements can be met before committing to a Treatment Table 7.

Source: US Navy (1985)

U.S. Navy Treatment Table 1A



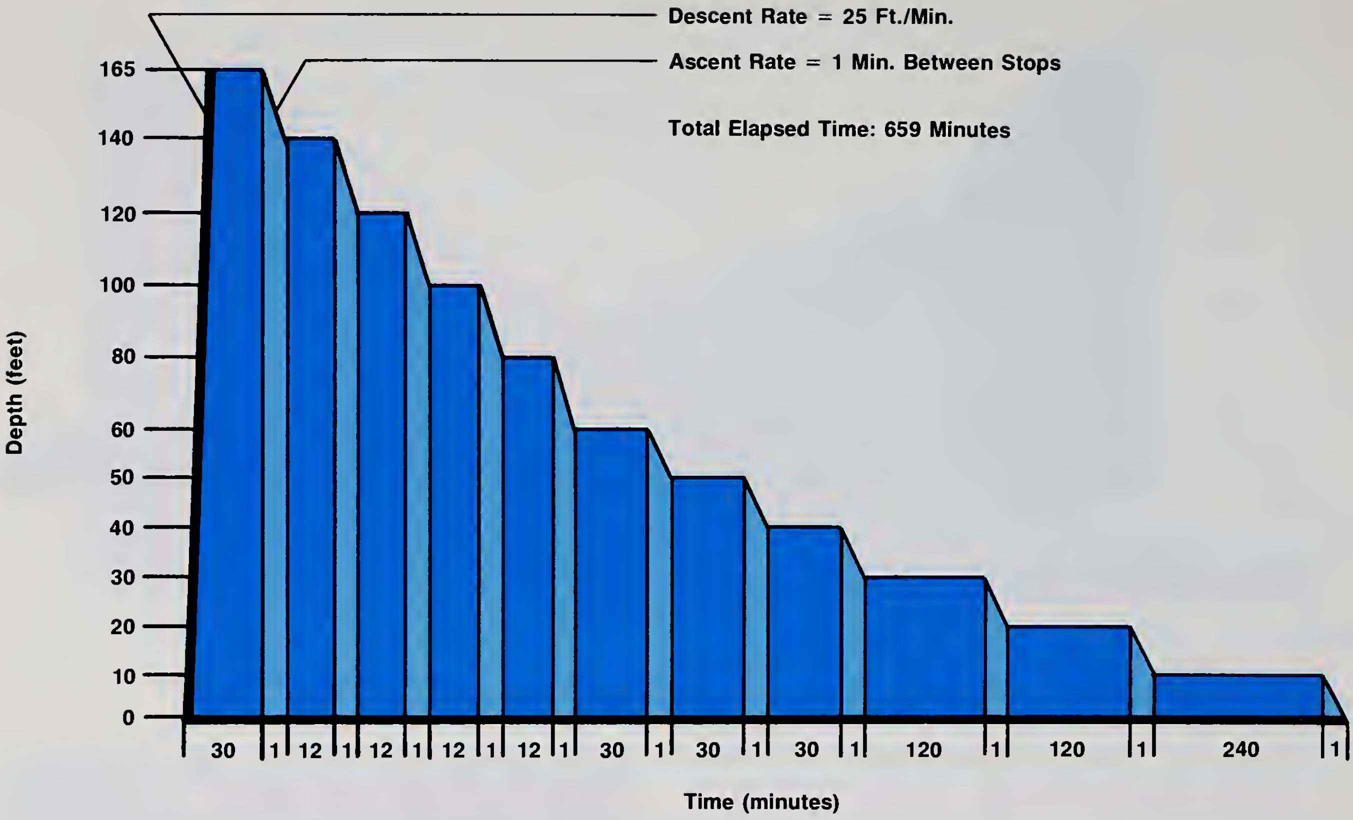
AIR TREATMENT OF TYPE I DECOMPRESSION SICKNESS—100-FOOT TREATMENT

1. Treatment of Type I decompression sickness when oxygen unavailable and pain is relieved at a depth less than 66 feet.
2. Descent rate—25 ft/min.
3. Ascent rate—1 minute between stops.
4. Time at 100 feet—includes time from the surface.
5. If the piping configuration of the chamber does not allow it to return to atmospheric pressure from the 10 foot stop in the 1 minute specified, disregard the additional time required.

Depth (feet)	Time (minutes)	Breathing Media	Total Elapsed Time (hrs:min.)
100	30	Air	0:30
80	12	Air	0:43
60	30	Air	1:14
50	30	Air	1:45
40	30	Air	2:16
30	60	Air	3:17
20	60	Air	4:18
10	120	Air	6:19
0	1	Air	6:20

Source: US Navy (1985)

U.S. Navy Treatment Table 2A



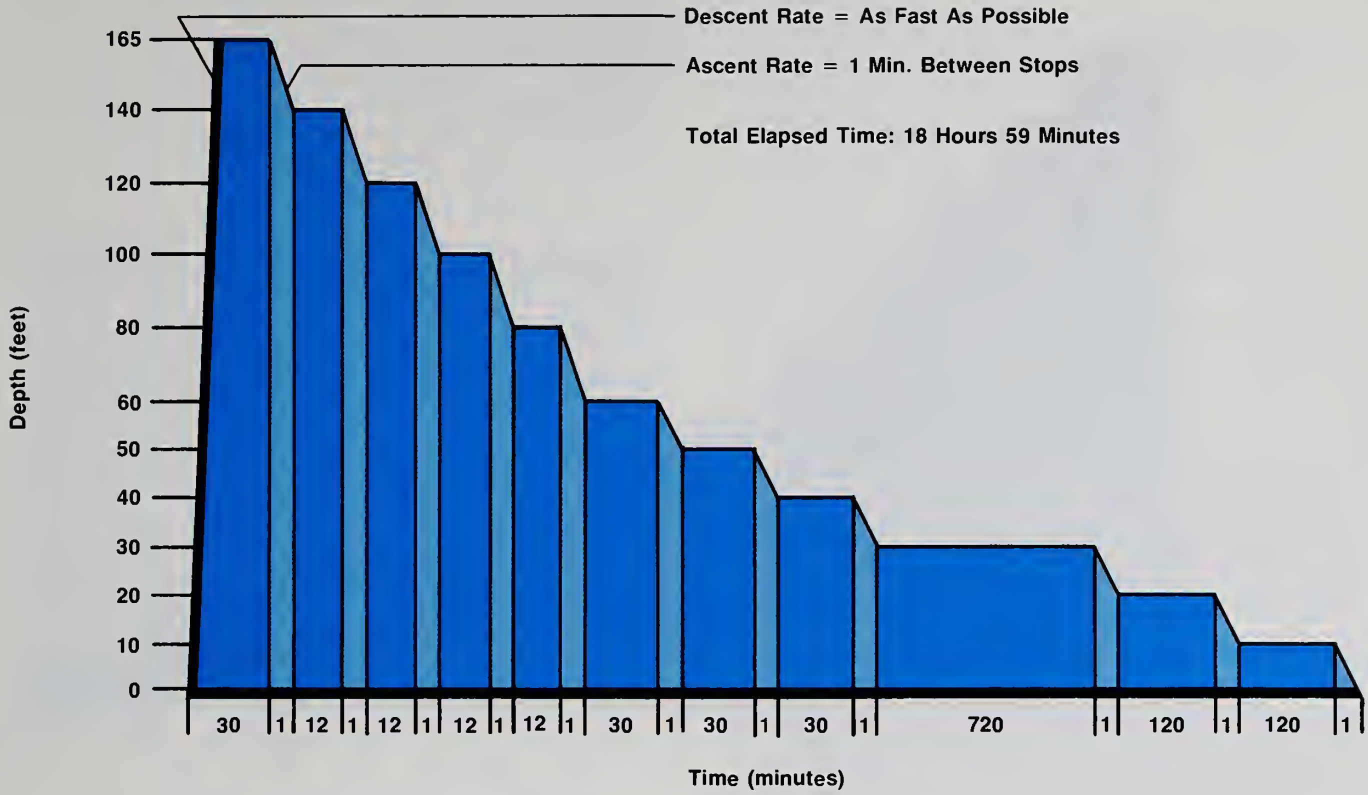
AIR TREATMENT OF TYPE I DECOMPRESSION SICKNESS—165-FOOT TREATMENT

1. Treatment of Type I decompression sickness when oxygen unavailable and pain is relieved at a depth greater than 66 feet.
2. Descent rate—25 ft/min.
3. Ascent rate—1 minute between stops.
4. Time at 165 feet—includes time from the surface.

Depth (feet)	Time (minutes)	Breathing Media	Total Elapsed Time (hrs:min.)
165	30	Air	0:30
140	12	Air	0:43
120	12	Air	0:56
100	12	Air	1:09
80	12	Air	1:22
60	30	Air	1:53
50	30	Air	2:24
40	30	Air	2:55
30	120	Air	4:56
20	120	Air	6:57
10	240	Air	10:58
0	1	Air	10:59

Source: US Navy (1985)

U.S. Navy Treatment Table 3



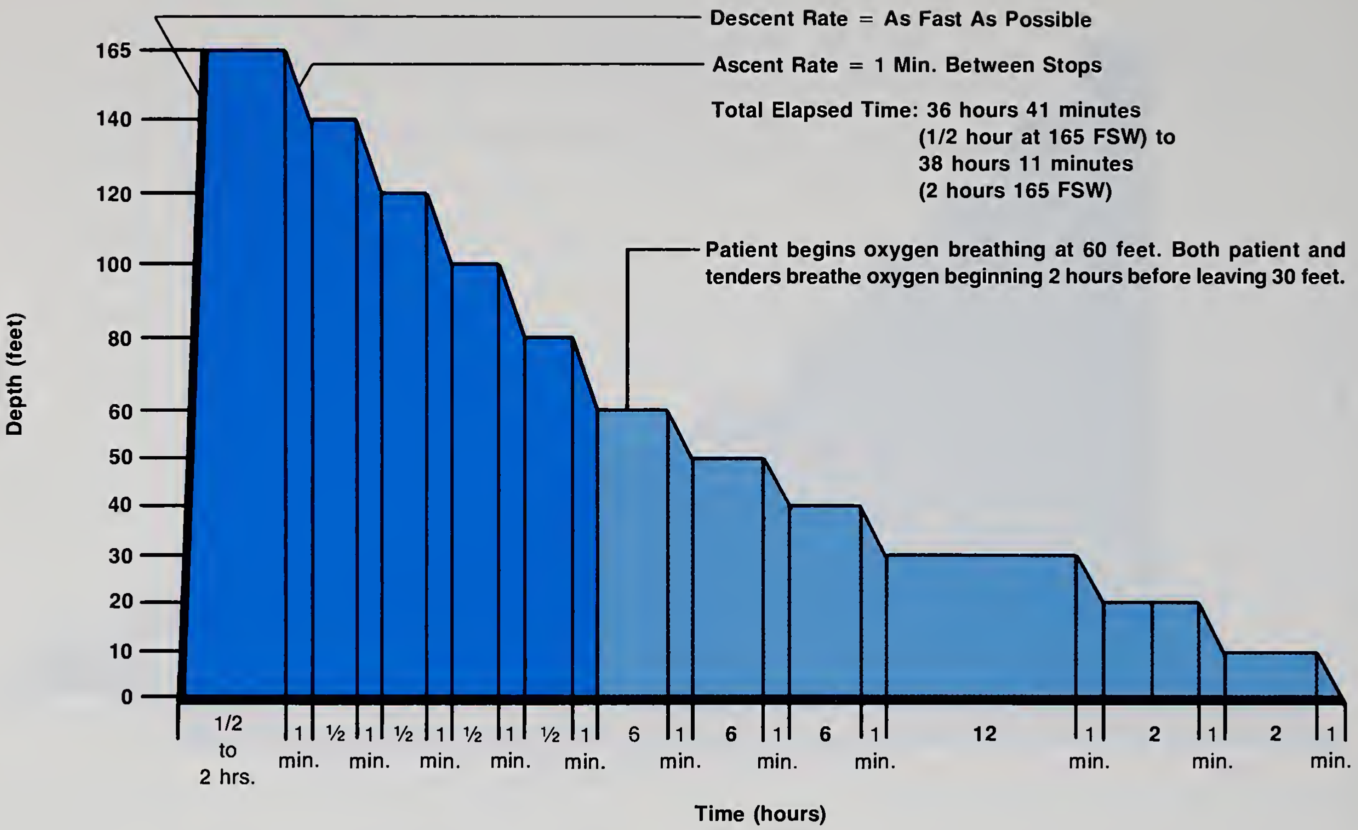
AIR TREATMENT OF TYPE II DECOMPRESSION SICKNESS OR ARTERIAL GAS EMBOLISM

1. Treatment of Type II symptoms of arterial gas embolism when oxygen unavailable and symptoms are relieved within 30 minutes at 165 feet.
2. Descent rate—as rapidly as possible.
3. Ascent rate—1 minute between stops.
4. Time at 165 feet—include time from the surface.

Depth (feet)	Time (minutes)	Breathing Media	Total Elapsed Time (hrs:min.)
165	30 min.	Air	0:30
140	12 min.	Air	0:43
120	12 min.	Air	0:56
100	12 min.	Air	1:09
80	12 min.	Air	1:22
60	30 min.	Air	1:53
50	30 min.	Air	2:24
40	30 min.	Air	2:55
30	720 min.	Air	14:56
20	120 min.	Air	16:57
10	120 min.	Air	18:58
0	1 min.	Air	18:59

Source: US Navy (1985)

U.S. Navy Treatment Table 4



AIR OR AIR AND OXYGEN TREATMENT OF TYPE II DECOMPRESSION SICKNESS OR ARTERIAL GAS EMBOLISM

1. Treatment of worsening symptoms during the first 20-minute oxygen breathing period at 60 feet on Table 6, or when symptoms are not relieved within 30 minutes at 165 feet using air treatment Table 3 or 6A.
2. Descent rate—as rapidly as possible.
3. Ascent rate—1 minute between stops.
4. Time 165 feet—includes time from the surface.
5. If only air available, decompress on air. If oxygen available, patient begins oxygen breathing upon arrival at 60 feet with appropriate air breaks. Both tender and patient breathe oxygen beginning 2 hours before leaving 30 feet.
6. Ensure life support considerations can be met before committing to a Table 4. Internal chamber temperature should be below 85°F.
7. If oxygen breathing is interrupted, no compensatory lengthening of the table is required.
8. If switching from Treatment Table 6A at 165 feet, stay the full 2 hours at 165 feet before decompressing.

Depth (feet)	Time (minutes)	Breathing Media	Total Elapsed Time (hrs:min.)
165	½ to 2 hr.	Air	2:00
140	½ hr.	Air	2:31
120	½ hr.	Air	3:02
100	½ hr.	Air	3:33
80	½ hr.	Air	4:04
60	6 hr.	Air or Oxygen/Air	10:05
50	6 hr.		16:06
40	6 hr.		22:07
30	12 hr.		34:08
20	2 hr.		36:09
10	2 hr.		38:10
0	1 min.		38:11

COMEX Treatment Table CX 30

1. Use—treatment of vestibular and general neurological decompression sickness occurring after either a normal or shortened decompression.
2. Descent rate—as quickly as possible (2 or 3 minutes).
3. Ascent rate—between 100 and 80 fsw—1.5 min/ft.
   —between 80 and 60 fsw—1.5 min/ft.
4. Time at 100 fsw does not include compression time.

Depth (fsw)	Time (minutes)	Breathing Medium	Total Elapsed Time (hrs:min)
100	40	50-50**	0:43
100-80	5	Air	
	25	50-50	1:13
80	5	Air	1:18
80	25	50-50	1:43
80-60	5	Air	
	25	50-50	2:13

** Helium/Oxygen or Nitrogen/Oxygen

Source: C. Gordon Daugherty (1983)

COMEX Treatment Table CX 30A

1. Use—treatment of musculoskeletal decompression sickness when signs of oxygen poisoning are present.
2. Descent rate—as quickly as possible (2 to 3 minutes), using air.
3. Ascent rate—continuous ascent at the rates shown below.
4. Time at 100 fsw does not include compression time.

Depth (fsw)	Time (minutes)	Breathing Medium	Total Elapsed Time (hrs:min)
100	60	Air	1:03
100-80	6	Air	1:09
80-70	60	Air	2:09
70-60	66	Air	3:15

Source: C. Gordon Daugherty (1983)

Royal Navy Treatment Tables 71 and 72

1. Maximum pressures may be less than the above depths.
2. Descent rate—33 ft/min.
3. Ascent by continuous bleed. If rate is slowed, it must not be compensated for by subsequent acceleration. The ascent should be halted if rate is exceeded or if the rate cannot be controlled accurately during flushing of chamber.
4. Oxygen may be administered periodically in selected cases, as advised.
5. Time at maximum pressure does not include compression time.

Depth (fsw)	Stops/ Ascent	Rate of Ascent (ft/hr)
	Royal Navy Table 71	
230	30 min.	
230-208	7 min.	198
208-168	2 hrs.	20
168-129	4 hrs.	10
129-96	5 hrs.	6
96-66	6 hrs.	5
66-33	10 hrs.	3
33-0	20 hrs.	1.6
	Royal Navy Table 72	
165	2 hrs.**	
164-129 (then as Table 71)	3 hrs. 40 min.	10

** This period can be reduced if symptoms clear earlier.

Source: C. Gordon Daugherty (1983)

Lambertsen/Solus Ocean Systems Treatment Table 7A

1. Use—for symptoms under pressure, for recompression deeper than 165 fsw, or where extended decompression is necessary.
2. Descent rate—as fast as possible, at least 25 fsw per minute.
3. Ascent rate—varies according to treatment depth; refer to schedule. Do not compensate for slower rates; for faster rates, halt the ascent.

4. If oxygen breathing must be interrupted, allow 30 minutes after reaction subsides and resume schedule at point of interruption.
5. Patient is held at treatment depth for 30 minutes as follows:
   a) On air—limit depth to 200 fsw, stay 30 minutes, go to 165 fsw in 1 minute, and then follow table.
   b) On He/O_2—go to depth of relief plus 33 fsw but not deeper than the dive. Hold 30 minutes, then go to 165 fsw at 15 fsw per hour (4 min. per foot), and then follow table.

Depth (fsw)	Ascent Rate	Chamber Atmosphere	Breathing Gas	Time (hrs:min)
Final treatment depth (See 5, above)	Varies (See 5, above)	Air or He/O_2	Chamber atmosphere, according to depth	30 min. +ascent to 165 ft.
165 to 150	15 ft/hr. (4 min/(ft.)	Air	Air	1:00
150 to 100	10 ft/hr. (6 min/ft.)	Air	Air	5:00
100 to 70	6 ft/hr. (10 min/ft.)	Air	Residual symptoms and 50-50 nitrox available; 5 cycles of 30 min. nitrox, 30 min. air. Otherwise, breathe air.	5:00
70 to 60	4 ft/hr. (15 min/ft.)	Air	Air	2:30
60 to 40	4 ft/hr. (15 min/ft.)	Air	5 cycles of 30 min. O_2, 30 min. air	5:00
40 to 30	4 ft/hr. (15 min/ft.)	Air	Air	2:30
30 to 20	2 ft/hr. (30 min/ft.)	Air	5 cycles of 30 min. O_2, 30 min. air (both patient and tender)	5:00
20 to 10	2 ft/hr. (30 min/ft.)	Air	Air	5:00
10 to 2	2 ft/hr. (30 min/ft.)	Air	4 cycles of 30 min. O_2, 30 min. air	4:00
2 to 0	2 ft/hr. (30 min/ft.)	Air	Oxygen	1:00

Total Time 165 Feet to Surface = 36:00

Source: C. Gordon Daugherty (1983)

Modified NOAA Nitrox Saturation Treatment Table

1. Total decompression time—55 hrs. 30 min.
2. Decompression time between stops = 10 minutes.

Depth (fsw)	Time at Stop (hrs:min)	Breathing Mixture
100	30 min. to 90 ft.	Air
90	00:50	Air
85	01:20	Air
80	01:30	Air
75	01:40	Air
70	01:50	Air
65	02:00	Air
60	06:00	Air
55	02:20	Air
50	02:40	Air
45	02:40	Air
40	00:10	Oxygen
40	02:30	Air
35	02:30	Air
30	12:00	Air
25	02:00	Oxygen/Air**
20	02:20	Air
15	02:40	Oxygen/Air**
10	02:30	Air
5	02:40	Air

** Oxygen delivered in 4 recurrent cycles—25 min. O_2/5 min. air.

Source: C. Gordon Daugherty (1983)

APPENDIX D
NOAA NITROX I DIVING AND DECOMPRESSION TABLES

APPENDIX D

NOAA NITROX I DIVING AND DECOMPRESSION TABLES

WARNING

NOAA Nitrox I Tables May Be Used Only With Open-Circuit Breathing Equipment and When Breathing a Mixture of 68 Percent Nitrogen and 32 Percent Oxygen

NOAA Nitrox I is a standard breathing gas mixture of 32% oxygen (±1%); the balance of the gas (68%) is nitrogen. Use of this gas mixture significantly increases the amount of time a diver can spend at depth without decompression, and it may be used in routine diving operations when it is advantageous. All oxygen partial pressure-time combinations for use with this mixture, except where noted, are within the normal oxygen exposure limits given in Table 15-1.

The following limitations are placed on the use of NOAA Nitrox I:

- All gases used in Nitrox I diving must be of breathing quality.
- NOAA Nitrox I gas may be used only in standard open-circuit breathing equipment.
- High-pressure storage cylinders, scuba tanks, regulators, and all high-pressure gas transfer equipment that is used with pure oxygen or with nitrox mixtures that contain more than 40 percent oxygen must be cleaned and maintained for oxygen service.
- The normal depth limit for use of this mixture shall be 130 feet of seawater for dives that do not require decompression.
- All NOAA divers who use NOAA Nitrox I must be trained and certified in its use by the NOAA Diving Coordinator.

Table D-1 NOAA Nitrox I (68% N_2, 32% O_2) No-Decompression Limits and Repetitive Group Designation Table for No-Decompression Dives

Depth, fsw	No-decompression limits, min	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
15		60	120	210	300											
20		35	70	110	160	225	350									
25		25	50	75	100	135	180	240	325							
30		20	35	55	75	100	125	160	195	245	315					
40		15	30	45	60	75	95	120	145	170	205	250	310			
45	310	5	15	25	40	50	60	80	100	120	140	160	190	220	270	310
50	200	5	15	25	30	40	50	70	80	100	110	130	150	170	200	
60	100		10	15	25	30	40	50	60	70	80	90	100			
70	60		10	15	20	25	30	40	50	55	60					
80	50		5	10	15	20	30	35	40	45	50					
90	40		5	10	15	20	25	30	35	40						
100	30		5	10	12	15	20	25	30							
110	25		5	7	10	15	20	22	25							
120	25		5	7	10	15	20	22	25							
130	20			5	10	13	15	20								
140	15			5	10	12	15									
150	10			5	8	10										

Table D-2 NOAA Nitrox I (68% N_2, 32% O_2) Decompression Table

Depth, fsw	Bottom Time, min	Time First Stop, min:sec	Decompression Stops, fsw					Total Ascent, min:sec	Repetitive Group
			50	40	30	20	10		
50	200	0:40					0	0:50	*
	210	0:40					2	2:50	N
	230	0:40					7	7:50	N
	250	0:40					11	11:50	O
	270	0:40					15	15:50	O
	300	0:40					19	19:50	Z
	360	0:40					23	23:50	**
60	100						0	1:00	*
	110	0:50					3	4:00	L
	120	0:50					5	6:00	M
	140	0:50					10	11:00	M
	160	0:50					21	22:00	N
	180	0:50					29	30:00	O
	200	0:50					35	36:00	O
	220	0:50					40	41:00	Z
	240	0:50					47	48:00	Z
70	60						0	1:10	*
	70	0:60					2	3:10	K
	80	0:60					7	8:10	L
	100	0:60					14	15:10	M
	120	0:60					26	27:10	N
	140	0:60					39	40:10	O
	160	0:60					48	49:10	Z
	180	0:60					56	57:10	Z
	200	0:50				1	69	71:10	Z
	240	0:50				2	79	82:10	**
80	50						0	1:20	*
	60	1:10					8	9:20	K
	70	1:10					14	15:20	L
	80	1:10					18	19:20	M
	90	1:10					23	24:20	N
	100	1:10					33	34:20	N
	110	1:00				2	41	44:20	O
	120	1:00				4	47	52:20	O
	130	1:00				6	52	59:20	O
	140	1:00				8	56	65:20	Z
	150	1:00				9	61	71:20	Z
	160	1:00				13	72	86:20	Z
	170	1:00				19	79	99:20	Z

* See No Decompression Table for repetitive groups

** Repetitive dives may not follow exceptional exposure dives

*** Oxygen partial pressure exceptional exposure

Table D-2 NOAA Nitrox I (68% N_2, 32% O_2) Decompression Table—Continued

Depth, fsw	Bottom Time, min	Time First Stop, min:sec	Decompression Stops, fsw 50	40	30	20	10	Total Ascent, min:sec	Repetitive Group
90	40						0	1:30	*
	50	1:20					10	11:30	K
	60	1:20					17	18:30	L
	70	1:20					23	24:30	M
	80	1:10				2	31	34:30	N
	90	1:10				7	39	47:30	N
	100	1:10				11	46	58:30	O
	110	1:10				13	53	67:30	O
	120	1:10				17	56	74:30	Z
	130	1:10				19	63	83:30	Z
	140	1:10				26	69	96:30	Z
	150	1:10				32	77	110:30	Z
100	30						0	1:40	*
	40	1:30					7	8:40	J
	50	1:30					18	19:40	L
	60	1:30					25	26:40	M
	70	1:20				7	30	38:40	N
	80	1:20				13	40	54:40	N
	90	1:20				18	48	67:40	O
	100	1:20				21	54	76:40	Z
	110	1:20				24	61	86:40	Z
	120	1:20				32	68	101:40	Z
	130	1:10			5	36	74	116:40	Z
110	25						0	1:50	*
	30	1:40					3	4:50	I
	40	1:40					15	16:50	K
	50	1:30				2	24	27:50	L
	60	1:30				9	28	38:50	N
	70	1:30				17	39	57:50	O
	80	1:30				23	48	72:50	O
	90	1:20			3	23	57	84:50	Z
	100	1:20			7	23	66	97:50	Z
	110	1:20			10	34	72	117:50	Z
	120	1:20			12	41	78	132:50	Z
120	25						0	2:00	*
	30	1:50					3	5:00	I
	40	1:50					15	17:00	K
	50	1:40				2	24	28:00	L
	60	1:40				9	28	39:00	N
	70	1:40				17	39	58:00	O
	80	1:40				23	48	73:00	O
	90	1:30			3	23	57	85:00	Z
	100	1:30			7	23	66	98:00	Z
	110	1:30			10	34	72	118:00	Z
	120	1:30			12	41	78	133:00	Z

* See No Decompression Table for repetitive groups

** Repetitive dives may not follow exceptional exposure dives

*** Oxygen partial pressure exceptional exposure

Table D-2 NOAA Nitrox I (68% N_2, 32% O_2) Decompression Table—Continued

Depth, fsw		Bottom Time, min	Time First Stop, min:sec	Decompression Stops, fsw					Total Ascent, min:sec	Repetitive Group
				50	40	30	20	10		
130		20						0	2:10	*
		25	2:00					3	5:10	H
		30	2:00					7	9:10	J
		40	1:50				2	21	25:10	L
		50	1:50				8	26	36:10	M
		60	1:50				18	36	56:10	N
		70	1:40			1	23	48	74:10	O
		80	1:40			7	23	57	89:10	Z
		90	1:40			12	30	64	108:10	Z
	***	100	1:40			15	37	72	126:10	Z
140	***	15						0	2:20	*
		20	2:10					2	4:20	H
		25	2:10					6	8:20	I
		30	2:10					14	16:20	J
		40	2:00				5	25	32:20	L
		50	2:00				15	31	48:20	N
		60	1:50			2	22	45	71:20	O
		70	1:50			9	23	55	89:20	O
150	***	10						0	2:30	*
		15	2:20					1	3:30	F
		20	2:20					4	6:30	H
		25	2:20					10	12:30	J
		30	2:10				3	18	23:30	M
		40	2:10				10	25	37:30	N
		50	2:00			3	21	37	63:30	O
		60	2:00			9	23	52	86:30	Z

* See No Decompression Table for repetitive groups

** Repetitive dives may not follow exceptional exposure dives

*** Oxygen partial pressure exceptional exposure

Table D-3 Residual Nitrogen Times for NOAA Nitrox I (68% N_2, 32% O_2) Dives

Repetitive Dive Depth, fsw	Repetitive Group Designation															
	Z	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
50	257	241	213	187	161	138	116	101	87	73	61	49	37	25	17	7
60	169	160	142	124	111	99	87	76	66	56	47	38	29	21	13	6
70	122	117	107	97	88	79	70	61	52	44	36	30	24	17	11	5
80	100	96	87	80	72	64	57	50	43	37	31	26	20	15	9	4
90	84	80	73	68	61	54	48	43	38	32	28	23	18	13	8	4
100	73	70	64	58	53	47	43	38	33	29	24	20	16	11	7	3
110	64	62	57	52	48	43	38	34	30	26	22	18	14	10	7	3
120	64	62	57	52	48	43	38	34	30	26	22	18	14	10	7	3
130	57	55	51	47	42	38	34	31	27	24	20	16	13	10	6	3
140	52	50	46	43	39	35	32	28	25	21	18	15	12	9	6	3
150	46	44	40	38	35	31	28	25	22	19	16	13	11	8	6	3

Values are minutes.

Table D-4 Residual Nitrogen Timetable for Repetitive NOAA Nitrox I (68% N_2, 32% O_2) Dives*

Repetitive groups at the beginning of the surface interval

A																0:10 12:00 *
B															0:10 2:10	2:11 12:00 *
C														0:10 1:39	1:40 2:49	2:50 12:00 *
D													0:10 1:09	1:10 2:38	2:39 5:48	5:49 12:00 *
E												0:10 0:54	0:55 1:57	1:58 3:22	3:23 6:32	6:33 12:00 *
F											0:10 0:45	0:46 1:29	1:30 2:28	2:29 3:57	3:58 7:05	7:06 12:00 *
G										0:10 0:40	0:41 1:15	1:16 1:59	2:00 2:58	2:59 4:25	4:26 7:35	7:36 12:00 *
H									0:10 0:36	0:37 1:06	1:07 1:41	1:42 2:23	2:24 3:20	3:21 4:49	4:50 7:59	8:00 12:00 *
I								0:10 0:33	0:34 0:59	1:00 1:29	1:30 2:02	2:03 2:44	2:45 3:43	3:44 5:12	5:13 8:21	8:22 12:00 *
J							0:10 0:31	0:32 0:54	0:55 1:19	1:20 1:47	1:48 2:20	2:21 3:04	3:05 4:02	4:03 5:40	5:41 8:40	8:41 12:00 *
K						0:10 0:28	0:29 0:49	0:50 1:11	1:12 1:35	1:36 2:03	2:04 2:38	2:39 3:21	3:22 4:19	4:20 5:48	5:49 8:58	8:59 12:00 *
L					0:10 0:26	0:27 0:45	0:46 1:04	1:05 1:25	1:26 1:49	1:50 2:19	2:20 2:53	2:54 3:36	3:37 4:35	4:36 6:02	6:03 9:12	9:13 12:00 *
M				0:10 0:25	0:26 0:42	0:43 0:59	1:00 1:18	1:19 1:39	1:40 2:05	2:06 2:34	2:35 3:08	3:09 3:52	3:53 4:49	4:50 6:18	6:19 9:28	9:29 12:00 *
N			0:10 0:24	0:25 0:39	0:40 0:54	0:55 1:11	1:12 1:30	1:31 1:53	1:54 2:18	2:19 2:47	2:48 3:22	3:23 4:04	4:05 5:03	5:04 6:32	6:33 9:43	9:44 12:00 *
O		0:10 0:23	0:24 0:36	0:37 0:51	0:52 1:07	1:08 1:24	1:25 1:43	1:44 2:04	2:05 2:29	2:30 2:59	3:00 3:33	3:34 4:17	4:18 5:16	5:17 6:44	6:45 9:54	9:55 12:00 *
	0:10 0:22	0:23 0:34	0:35 0:48	0:49 1:02	1:03 1:18	1:19 1:36	1:37 1:55	1:56 2:17	2:18 2:42	2:43 3:10	3:11 3:45	3:46 4:29	4:30 5:27	5:28 6:56	6:57 10:05	10:06 12:00 *
New Group Designation	Z	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A

*Dives after surface intervals of more than 12 hours are not repetitive dives. Use actual bottom times in the NOAA Nitrox I (68% N_2,32% O_2) Decompression Table to compute decompression for such dives.

APPENDIX E
GLOSSARY

Abducens Nerve	The sixth cranial nerve; controls the external rectus muscles of the eye.
ACFM	An abbreviation for actual cubic feet per minute.
Acidosis	Acid poisoning caused by the abnormal production and accumulation of acids in the body.
Acoustic Grid	A method for determining the position of an object relative to a fixed network of transponders.
Acoustic (Auditory) Nerve	The eighth cranial nerve; controls hearing.
Acoustic Relief	A discontinuity, such as a wreck or rock outcrop on the seafloor, that alters the reflection of an acoustic signal in a way that makes the object distinguishable from the surrounding area.
Adsorption	A type of adhesion that occurs at the surface of a solid or a liquid that is in contact with another medium; an example of adsorption occurs when dirt adsorbs or adheres to the hands.
Alidade	An indicator or sighting instrument used to determine direction and range for topographic surveying and mapping.
Alimentary Canal	The muscular-membranous tube, about 30 feet (9.1 meters) in length, that extends in animals and humans from the mouth to the anus.
Alternobaric Vertigo	Dizziness caused by asymmetric clearing of the middle ear during ascent or descent.
Alveolus	A small membranous sac in the lungs in which gas exchange takes place.
Ama Divers	Female pearl divers of Japan known for their ability to make deep and long breath-hold dives and to tolerate cold water.
Amniotic Fluid	The serous fluid within the sac (amnion) that encloses a fetus.
Amphibious Camera	A camera that needs no special housing for underwater photography because all ports, lids, and control rods on the camera are O-ring sealed.
Analgesic	A medication that reduces or eliminates pain.
Angiosperm	A plant whose seeds are enclosed in an ovary; a flowering plant.
Anorexia	The absence of appetite.
Anoxia	The absence of oxygen (*see* Hypoxia).
Antigen	Any bacterium or substance which, when injected into an organism, is capable of causing the formation of an antibody.
Aortic Stenosis	Constriction or narrowing of the aortic artery.
Aperture	In photography, the opening that regulates the amount of light passing through a camera lens (*see* f Stop).
Aphakia	The absence of a lens in the eye.
Aphasia	Partial or complete loss of the ability to express ideas in speech or writing.
Apnea	A brief cessation of breathing.
Apoplexy	The name given to the complex of symptoms and signs caused by hemorrhage or blockage of the brain or spinal cord. This term is also applied to the signs and symptoms resulting from bursting of a vessel in the lungs, liver, etc. Apoplexy can cause both physical and mental signs and symptoms and can be fatal.
Arthralgia	Pain that occurs in the joints during compression or decompression.
ASA Film Speed (ASA ISO)	In photography, a number referring to a film's sensitivity to light. This number can be used, along with the readout from an exposure meter, to determine camera settings for aperture and shutter speed.

Aseptic Bone Necrosis	*See* Osteonecrosis.
Asphyxia	Anoxia caused by the cessation of effective gas exchange in the lung.
Aspirator	A device used to remove liquids or gases from a space by suction.
Atherosclerosis	Thickening of the outer layers of an artery and degeneration of the artery's elastic layer.
Atmospheric Diving System	A pressure-resistant one-man diving system that has articulated arms and sometimes legs and that is both equipped with life support capability and designed to operate at an internal pressure of one atmosphere.
Audiometer	An instrument used to measure hearing thresholds for pure tones at normal frequencies.
Automatic Exposure Control	A control on a camera that presets an exposure for aperture (f stop) and controls the light reaching the film via a shutter.
Autonomic Dysreflexia	A physiologic response that may occur in a person with certain spinal cord injuries and that can be triggered by any irritating stimulus, such as a full bladder; autonomic dysreflexia can lead to elevated blood pressure, reduced heart rate, seizures, unconsciousness, and death.
Autowinder	An electrical or spring-driven motor that automatically advances the film after the shutter is triggered.
A-V (Arteriovenous) Shunt	A link between an artery and a vein that may be congenital, occur spontaneously, or be created surgically. It can cause blood to flow prematurely from one vessel to another.
Babinski Reflex	A reflex characterized by extension of the big toe and flexion of the other toes; the existence of the Babinski reflex indicates spinal cord involvement.
Backscatter	In photography, light that is reflected back toward the camera lens by particles suspended in the water.
Barodontalgia	Pain in the teeth that is caused by changes in barometric pressure.
Barotitis Media	Also called "middle ear squeeze." Barotitis media is an inflammation of the middle ear that is caused by inadequate pressure equalization between the middle ear and the ambient atmosphere.
Barotrauma	Mechanical damage to or distortion of tissues that is caused by unequal pressures.
Bathymetry	The art or science of determining or measuring depths of water.
Bed Forms	A geologic feature of the seafloor caused by environmental dynamics, such as near-bottom or wave-induced currents.
Bends	A colloquial term meaning any form of decompression sickness.
Benthic	An adjective referring to the benthos, or seafloor. Plants and animals that live on the seafloor are benthic organisms.
Beta Blockers	Drugs used to treat a variety of conditions, including cardiovascular problems. A prominent effect of these drugs is a reduction in heart rate, which causes, in turn, a reduction in cardiac output and oxygen consumption by the heart muscles.
Biomass	The amount of organic matter per given volume.
Blowup	The uncontrolled ascent of a diver who is wearing a deep sea diving suit or a variable-volume dry suit.
Boundary Layer	The thin layer of higher viscosity or drag around a stationary body or in a stationary conduit that is created by the motion of a fluid of low viscosity, such as air or water.
Bradycardia	Slowness of the heart beat, which is evidenced by slowing of the pulse to 60 beats a minute or less.
Brisance	The shattering effect of a sudden release of energy, such as occurs in an explosion.
Bronchi	Fibro-muscular tubes connecting the trachea to the smaller portions of the respiratory tract.

Bronchospasm	A sudden and involuntary contraction of the bronchial tubes.
Carapace	A hard bony or chitinous outer covering; examples of carapaces are the fused dorsal plates of a turtle or the portion of the exoskeleton covering the head and thorax of a crustacean.
Carboxy-hemoglobin	The compound of carbon monoxide (CO) and hemoglobin that is formed when CO is present in the blood.
Carotid Artery	The principal artery on each side of the neck in humans.
Carrier Wave	An electric wave that can be modulated to transmit signals in radio, telephonic, or telegraphic systems.
Cathodic Protection	A technique designed to reduce the corrosion that occurs in seawater as a result of the presence of dissimilar metals; when cathodic protection is used, a sacrificial metal is introduced to serve as the anode (site of corrosion), which protects nearby metal parts.
Cerebellum	The part of the brain that lies below the cerebrum and is concerned with the regulation and control of voluntary muscular movement.
Cervical Spine	The upper seven vertebrae of the spinal cord.
Chokes	An imprecise term for the pulmonary symptoms of decompression sickness.
Cholecystitis	Inflammation of the gall bladder.
Clavicle	The collar bone.
Close-Up Attachment	In photography, a close-up lens that fits over the primary lens of a camera.
Closed-Circuit Breathing System	A life support system or breathing apparatus in which the breathing gas is recycled, carbon dioxide is removed, and oxygen is added to replenish the supply as necessary.
Coarctation	Compression of the walls of a vessel or canal.
Cochlea	A snail-shaped cavity in the temporal bone of the inner ear that contains the organ of hearing.
Coelenterata	A phylum of the animal kingdom comprised of hydroids, jellyfish, sea anemones, corals, and related animals. Most species are marine and all are aquatic.
Colitis	Inflammation of the colon.
Conductive Hearing Loss	A type of auditory defect caused by impairment of the conductive mechanism of the ear; such impairments can occur when the eardrum is damaged, air passages are blocked, or movement of the bones of the inner ear is impaired.
Constant-Volume Dry Suit	A dry diving suit designed to be partially inflated to prevent squeeze and to provide insulation against cold.
Contrast	In photography, the difference between the brightest and darkest areas in a photograph.
Copepod	A small planktonic crustacean that is usually less than 2 millimeters in length.
Cornea	The transparent anterior portion of the eyeball.
Counterdiffusion	The movement of two inert gases in opposing directions through a semi-permeable membrane; when both gases are at the same pressure, the phenomenon is called isobaric counterdiffusion.
Cricothyroidotomy	Incision through the ring-shaped cartilage of the larynx.
Cryogenics	The production of low temperatures.
CU	In photography, a close-up shot that pinpoints the main action.
Cyanosis	A bluish discoloration of the skin, lips, and nail beds that is caused by an insufficiency of oxygen in the blood.
Dead Space	The space in a diving system in which residual exhaled air remains. The dead space in diving equipment adds to the amount of dead space that occurs naturally in human lungs.

Decompression Dive	Any dive involving a depth deep enough or a duration long enough to require controlled decompression, i.e., any dive in which ascent to the surface must be carried out through decompression stops.
Decompression Schedule	A set of depth-time relationships and instructions for controlling pressure reductions.
Decompression Sickness	An illness caused by the presence of bubbles in the joints or tissues; decompression sickness may occur after a reduction in barometric pressure.
Decompression Stop	The designated depth and time at which a diver must stop and wait during ascent from a decompression dive. The depth and time are specified by the decompression schedule being used.
Demersal Fish	Bottom-living fish, such as plaice or flounder.
Depth of Field	Term used in photography to denote the distance between the nearest and most distant objects that will be in focus.
Dermatitis	Inflammation of the skin.
Dip	A geological term for the angle in degrees between a horizontal plane and the inclined angle of a rockbed, as measured down from the horizontal in a plane perpendicular to the strike (*see* Strike).
Diverticulitis	Inflammation of a diverticulum, an outpouching of the colon that may occur in humans.
Doppler Bubble Monitor	A device that detects moving bubbles in the circulatory system by picking up changes in the frequency of sound reflected by moving objects.
Do-Si-Do Position	A position used in diver rescues on the surface that enables the rescuer to administer mouth-to-mouth resuscitation to an unconscious victim.
Dysbarism	A general term applied to any clinical condition caused by a difference between the surrounding atmospheric pressure and the total gas pressure in the various tissues, fluids, and cavities of the body.
Dyspnea	Difficulty in breathing.
Edema	Swelling of a part of the body that is caused by the buildup of fluid.
EEG	Abbreviation for electroencephalogram, a graphic record of the electrical activity of the brain made by an electroencephalograph.
Elastomer	A rubberlike material, such as neoprene or silicone rubber.
Electronic Flash	In photography, an electrical light source that emits a brief burst of light.
Embolism, Air or Gas	A bubble in the arterial system that occurs when gas or air passes into the pulmonary veins after rupture of air sacs of the lung.
Emphysema	A pulmonary condition characterized by loss of lung elasticity and restriction of air movement.
Emphysematous Bullae	Blebs or air-filled blisters in the lungs caused by emphysema.
Envenom	To poison or put venom into or onto something.
Epilimnion	The layer of water above a thermocline.
Epifauna	Marine animals that live on the surface of the seafloor.
Epiphytic Plants	Plants that are attached to or are supported by another plant but that obtain their food independently.
Equivalent Air Depth (EAD)	The air-breathing depth that has a nitrogen partial pressure that is equivalent to the nitrogen partial pressure at the diving depth.
Equivalent Single Dive Bottom Time	The bottom time that is equal to the sum of the residual nitrogen time and the actual bottom time of the dive.
Ester	A compound that reacts with water, acid, or alkali to form an alcohol plus an acid.

Eustachian Tube	The canal, partly bony and partly cartilaginous, that connects the throat (pharynx) with the middle ear (tympanic cavity) and that serves as an air channel to equalize pressure in the middle ear with pressure outside the ear.
Exceptional Exposure Dive	Any dive in which a diver is exposed to oxygen partial pressures, environmental conditions, or bottom times that are considered extreme.
Exposure	A term used in photography to denote the amount of light striking a film.
Exposure Meter	A meter that indicates the correct aperture and shutter speed combination for film exposure.
Exudation	The passing of material, e.g., serum or pus, through the wall of a vessel and into adjacent tissues.
f Number	(*See* f Stop).
f Stop	A number used in photography to refer to the relative diameter of the aperture; the higher the number, the smaller the aperture. Each consecutively higher-numbered stop admits half as much light as the previously numbered stop.
Facial Nerve	The seventh cranial nerve; controls motion of the face, ear, palate, and tongue.
Fathometer	An instrument used to measure the depth of water by determining the time required for a sound wave to travel from the surface to the bottom and for its echo to return to the surface.
Fenestrated	Perforated.
Fenestration	The cutting of an opening (window).
Fixed Focus Lens	A camera lens with a preset focal distance that cannot be changed.
Flapper (Flutter) Valve	A soft rubber tube collapsed at one end. When the ambient water pressure is greater than the air pressure within the valve, the valve remains collapsed. When the air pressure within the valve is greater than the ambient water pressure, the valve opens.
Flashpoint	The lowest temperature at which a combustible liquid or solid will generate enough vapor to ignite in air.
Focus	In photography, the sharpness of the image.
Gas Chromatograph	A laboratory instrument used to identify and measure closely related chemical substances.
Geodesy	The science of describing the size end shape of the earth in mathematical terms.
Glossopharyngeal Nerve	The ninth cranial nerve; controls sensation, motion, and taste associated with the tonsils, pharynx, middle ear, and tongue.
Glaucoma	A condition caused by increased fluid pressure in the eye.
Grand Mal Seizure	A major convulsion that involves unconsciousness, loss of motor control, jerking of the extremities, and biting of the tongue.
Ground Fault Interrupter	An electronic device that detects electrical leakage by comparing the current in a hot wire with the current in an accompanying neutral wire.
Half Time	The time required to reach 50 percent of a final state. In diving, a half time is the time required for a tissue to absorb or eliminate 50 percent of the equilibrium amount of inert gas.
Hedron	A geometric figure that has a given number of faces or surfaces. For example, a pentahedron has five faces or surfaces.
Heliox	A breathing mixture of helium and oxygen that is used at greater depths because it can be inhaled without narcotic effect.
Hematopoietic Tissues	Blood-producing tissues, such as the bone marrow.
Hemoglobin	The coloring matter of the red corpuscles of the blood; hemoglobin combines with oxygen, carbon dioxide, and carbon monoxide.
Hemoptysis	Spitting of blood from the larynx, trachea, bronchi, or lungs.

Hepatitis	Inflammation of the liver.
Herbarium	A collection of dried plants that are mounted and labeled in preparation for scientific use.
Herniated Nucleus Pulposis	A rupture of a disk in the spinal cord that is caused by degenerative changes or a trauma that compresses a nerve root or the cord itself.
High Pressure Nervous Syndrome (HPNS)	Neurological and physiological dysfunction that is caused by hyperbaric exposure, usually to helium. The signs and symptoms of HPNS include tremor, sleep difficulties, brain wave changes, visual disturbances, nausea, dizziness, and convulsions.
Holdfast	The rootlike structure at the base of a kelp that anchors the plant to the seafloor.
Hopcalite	A catalyst used in air compressors and breathing apparatus to remove carbon monoxide or other gases.
Hypercapnia	A condition characterized by excessive carbon dioxide in the blood and/or tissues; hypercapnia causes overactivity of the respiratory center.
Hyperoxia	A condition characterized by excessive oxygen in the tissues.
Hyperpnea	Panting or exaggerated respiration.
Hyperthermia	Elevation of the body temperature to levels above normal.
Hyperventilation	Rapid, unusually deep breathing at a rate greater than is necessary for the level of physical activity.
Hypoallergenic	An adjective given to materials that are not likely to cause allergic responses in contact with the skin.
Hypocapnia	A condition characterized by an unduly low amount of carbon dioxide in the blood; hypocapnia causes underactivity of the respiratory center.
Hypoglossal Nerve	The twelfth cranial nerve; controls movement of the tongue.
Hypolimnion	The layer of water below a thermocline.
Hypothalamus	The nerve center in the brain that influences certain bodily functions, such as metabolism, temperature regulation, and sleep.
Hypothermia	Reduction of the body's core temperature to a level below 98.6°F (37°C); hypothermia can be caused by environmental exposure to cold or by failure of the body's thermoregulatory system.
Hypovolemic Shock	A physiological condition that is caused by a reduction in the volume of intravascular fluid and that may cause a decrease in cardiac output.
Hypoxia	A condition characterized by tissue oxygen pressures that are below normal; hypoxia may be caused by breathing mixtures that are deficient in oxygen, by disease states, or by the presence of toxic gases such as carbon dioxide.
Inclinometer	In geology, an instrument for measuring the angle of inclination (slope).
Inert Gas Narcosis	*See* Narcosis.
Inert Gases	Gases that exhibit great stability and extremely low reaction rates; examples of inert gases are helium, neon, argon, krypton, xenon, and, sometimes, radon; these gases are called inert because they are not biologically active.
Infauna	Marine animals living within the seafloor sediment, such as worms and some clams.
Inguinal	In mammals, pertaining to the groin.
Inner Ear	That portion of the ear that is located within the confines of the temporal bone and that contains the organs of equilibrium and hearing.
In situ	In the natural or original place or position.
Interchangeable Lenses	In photography, lenses that can be attached and detached easily.

Intercooler	A component of an air compressor that is designed to cool the air and to cause water and oil vapors to condense and collect as the air passes through the air/liquid separator.
Internal Waves	Waves arising at an internal boundary that is formed between layers of water that have different densities; such an internal boundary occurs when a layer of warm surface water from a river runoff overlays a layer of salty or cold water.
Intracranial Surgery	Surgery within the skull.
Ischemia	A localized physiological condition that is characterized by a deficiency in the supply of oxygen to tissues and that is caused by a contraction of the blood vessels.
Isohedron	*See* Hedron.
Jocking Belt (Jockstrap)	A strap worn by divers to prevent the diving helmet from being lifted off the shoulders, especially during entry into the water. The strap passes between the diver's legs and is attached to the front and back of the weight belt, which, in turn, is linked to the helmet.
Keratitis	Inflammation of the cornea of the eye.
Kerf	A groove or notch made by a saw, ax, cutting torch, etc.
Laminar Flow	Nonturbulent flow of a fluid.
Larynx	The organ of the voice; the larynx is situated between the trachea and the base of the tongue.
Leeway	Movement of an object through the water as a result of the force of the wind.
Liveboating	A search, inspection, or survey technique in which one or two divers are towed behind a boat that is under way.
Lockout Submersible	A submersible that has one compartment for the pilot and/or observer that is maintained at a pressure of one atmosphere and another compartment that can be pressurized to ambient pressure so that divers can enter and exit (lock out) while under water.
Longshore Current	A current that is generated by waves that are deflected by the shore at an angle. Such currents run roughly parallel to the shoreline.
LORAN-C	A long range, high-precision navigation system in which hyperbolic lines of position are determined by measuring the difference in the time at which synchronized pulse signals are received from two fixed transmitters.
Lymphatic System	A system of vessels and glands, accessory to the blood vascular system, which conveys the lymph fluid throughout the body.
Manometer	An instrument for measuring the pressure of liquids and gases. In its simplest form, a manometer consists of a U-tube, one end of which is open to the atmosphere and the other end of which is open to the region where the pressure is to be measured. If the pressure in the two areas is different, the liquid will be higher in one leg of the tube than in the other.
Mass Spectrometer	A laboratory instrument that uses the masses of compounds to identify and quantitate them. The principle of spectrometry involves ionizing the substance and separating the resulting molecular and fragment ions by means of electric and magnetic fields.
Meckels Diverticulum	A congenital sac, resembling the appendix, that occurs naturally in 1-2 percent of the population. This sac is located in the lower intestine and can ulcerate, hemorrhage, or develop obstructions or infections.
Mediastinum	The space between the lungs and under the breastbone where the heart is located.
Mediastinal Emphysema	Excessive gas or air in the tissues below the breastbone and near the heart, major blood vessels, and trachea. Mediastinal emphysema is caused by air being forced into this area from the lungs.

Meniere's Disease	A disease of the middle ear that is characterized by vertigo, sudden deafness, and symptoms of apoplexy.
Metabolism	The phenomenon of transforming food into complex tissue-elements and changing complex substances into simple ones to produce energy.
Methemoglobinemia	The presence of methemoglobin in the blood; this condition can be caused by toxic agents that are ingested, inhaled, or absorbed.
Microbe	A living organism of very small size; the term is often used synonymously with bacterium.
Modulation	The process of varying a characteristic of one wave in accordance with that of another wave. Modulation can be achieved by varying the amplitude, frequency, or phase of the carrier wave.
Morbidity	A scientific term meaning disease or sickness.
Mucosa or Mucous Membranes	The tissues lining those body cavities and canals that are exposed to air.
Mushroom Valve	A type of poppet valve that has a disk-like head attached to a stem. The stem reciprocates in a valve guide under the action of a cam that bears against the end of the stem or that operates a tappet that, in turn, bears against the valve stem.
Myelofibrosis	A disease state in which the marrow is replaced by fibroplastic cells.
Myoclonic Jerking	A series of involuntary movements characterized by alternating contraction and relaxation of muscles.
Myringotomy	Incision of the tympanic membrane (eardrum).
Narcosis	A state of stupor or unconsciousness; in diving, it is caused by breathing certain gases at pressure. Gases vary in their narcotic potency and may interact with each other to produce effects that are greater than those produced individually. The signs and symptoms of narcosis include lightheadedness, loss of judgment, and euphoria.
Nasal Septum	The partition between the two nasal cavities in humans.
Neat's-Foot Oil	A light yellow oil obtained from the feet and shinbones of cattle.
Neck Dam (Seal)	A rubber skirt that is attached to some lightweight helmets instead of a breastplate. A neck dam is tapered to fit tightly around the neck like a collar.
Necrosis	The death of cells.
Nematocyst	A structure consisting of a flask-shaped body bearing barbs and a long slender filament that can be discharged by the stinging cells of coelenterates.
Neuropathy	Any disease of the nervous system.
Niggles	Mild pains that indicate decompression sickness and that begin to resolve within 10 minutes of onset.
Niskin Bottle	A water-sampling device that is designed to collect water samples in amounts ranging routinely from 1.8 quart (1.7 liter) to 31.7 quarts (30 liters). Niskin bottles also can be used in conjunction with reversing thermometers to record temperature and depth concurrently.
Nitrox Breathing Mixture	A breathing mixture containing nitrogen and oxygen in varying proportions. The amount of oxygen in the mixture can be increased to increase the no-decompression bottom time or it may be reduced to avoid oxygen poisoning during deep dives.
NOAA Nitrox-I	A mixed gas breathing mixture consisting of 68 percent nitrogen and 32 percent oxygen.
Noble Gases	Gases whose chemical structure is characterized by closed shells or subshells of electrons. These gases are also called inert gases.
No-Decompression Dive	A dive to depths shallow enough and for times short enough to permit the diver to return to the surface at a controlled rate without having to spend time at specified stops to allow inert gas to be eliminated from the body.

Nomogram	A graphic representation of mathematical relationships or laws.
Normal Ascent Rate	The ascent rate used under conventional or routine conditions; this rate is 60 feet (18.3 meters) per minute.
Normal Lens	A camera lens that covers an area of about 1.5 x 2.25 feet (45 x 68 cm) at a distance of 3 feet (0.9 m).
Normoxic	A breathing gas mixture that supplies a diver with the same partial pressure of oxygen as that prevailing in a "normal" atmosphere, i.e., about 0.21 ATA of oxygen, at any specific depth.
Nystagmus	A physiological condition characterized by repeated, involuntary, rapid movements of the eyes, usually in the horizontal plane but sometimes also in the vertical plane.
Oculomotor Nerve	The third cranial nerve; controls the movement of the eyes.
Olfactory Nerve	The first cranial nerve; controls the sense of smell.
Operculum	The plate covering the gills of a bony fish.
Optic Nerve	The second cranial nerve; controls sight.
Oropharyngeal Airway	That part of the airway in humans that consists of the mouth and the pharynx (*see* Pharynx).
Osteomyelitis	Inflammation of the bone marrow.
Osteonecrosis (Dysbaric Osteonecrosis)	The death of cells in the long bones, such as the humerus, femur, or tibia; osteonecrosis can be caused by exposure to compressed air at pressures greater than atmospheric pressure.
Otitis Externa	Inflammation or superficial infection of the auditory canal.
Otitis Media	Inflammation of the middle ear.
Otterboards	Door-shaped boards that are attached to trawling nets to keep the nets open during trawling.
Oval Window	The upper of two membrane-covered openings in the cochlea of the inner ear (*see* Cochlea).
Overboard Dump (Discharge) System	A system built into a hyperbaric chamber and that transfers exhaled gas out of the chamber.
Overlap	In photography, a term used to mean reshooting the same action from a different camera angle.
Oxyhemoglobin	Oxidized hemoglobin in the arterial blood.
Pancreatitis	Inflammation of the pancreas.
Paranasal Sinuses	The air-filled cavities in the cranial bones accessory to the nose; the paranasal sinuses comprise the frontal, sphenoidal, ethmoidal, and maxillary sinuses.
Paraparesis	Partial paraplegia.
Paraplegia	Loss of function, and occasionally of sensation, in the lower body.
Parenteral Drug Administration	Administration of drugs by a route other than oral, e.g., by subcutaneous or intravenous injection.
Paroxysmal Tachycardias	Periodic bouts of fast heart beats.
Partial Pressure	The proportion of the total pressure contributed to a mixture by a single gas in that mixture.
Patent	Open, as in "a patent airway."
Pathogenic Organisms	Organisms that produce disease.
Peduncle	Any stalklike structure that supports another structure or organ.
Pelagic Organisms	Plants and animals that live in the open sea and that are not associated with the shore or sea floor.
Perfusion	The passage of fluid through spaces.
pH	A measure of the acidity or alkalinity of a solution; a pH of 7 is neutral, while one with a pH of 1 to 4.5 is strongly acidic and one with a pH of 11.5 to 14 is strongly alkaline.
Pharynx	That portion of the digestive and respiratory tract situated back of the nose, mouth, and larynx and extending from the base of the skull to a point opposite the sixth vertical vertebra, where it becomes contiguous with the esophagus.

Phase Measurement System	A method for determining the position of an object on the seafloor that uses a single transponder placed on the object and three receiving elements located on the underside of the surface support platform.
Phonetically Balanced Word Lists	Lists of words that are selected to ensure that each list contains a balanced and equal cross-representation of speech sounds. These lists can then be read by experimental subjects, e.g., divers, to compare the effectiveness of different communication systems.
Photogrammetry	The application of photographic principles to the science of mapping; photogrammetry involves the use of special cameras to photograph the earth's surface to produce mosaic pictures or scale maps.
Photon	The basic unit (quantum) of the electromagnetic field; photons have zero mass, no electric charge, and an indefinitely long lifetime.
Photophobia	Literally, a fear of light; in practice, a disinclination or inability to use the eyes in strong light.
Phytoplankton	Minute marine plants that drift in the sea and are usually microscopic; phytoplankton are either single-celled or loose aggregates of a few cells.
Pinger	An underwater locating device that emits an acoustic signal.
Pituitary	A gland, located in humans at the base of the brain, that influences growth, metabolism, sexual cycles, and many other bodily functions.
Plane Table	A surveying instrument used to locate and map topographical features.
Plankton	Plant and animal organisms (usually microscopic) that float or drift in fresh or salt water.
Platelet	A component of blood that affects its ability to clot.
Pleura	The serous membrane that envelops the lung and lines the thoracic cavity.
Pneumatocysts	Hollow floats found at the base of the blades or fronds of certain kelp plants and that cause the fronds to float up to form a canopy.
Pneumofathometer	A hollow tube that has one end connected to a gauge at the surface and another end that is open under water. Pneumofathometers are used to measure the water pressure at the submerged end of the tube.
Pneumomediastinum	*See* Mediastinal emphysema.
Pneumothorax	The presence of gas within the chest cavity but outside the lungs.
Polycythemia	A condition characterized by an excessive number of corpuscles (usually red) in the blood.
Prosthesis	A man-made replacement for a missing body part.
Protozoa	One of the lowest classes of the animal kingdom, the protozoa are organisms that consist of simple cells or colonies of cells and that possess no nervous or circulatory system.
Provenance Data	The original data.
PSIG	Abbreviation for pounds per square inch gauge; a term used to express the difference between absolute pressure and the specific pressure being measured.
Psychosis	A disease of the mind characterized by loss of contact with reality.
Pulmonary	Pertaining to or affecting the lungs.
Pulmonary Edema	An accumulation of fluid in the lungs.
Purse Seine	A fishing net that is made to hang vertically in the water by weights at the lower edge and floats at the top and that is pursed or drawn into the shape of a bag to enclose the catch.
Pyrolytic Decomposition	Chemical change caused by heat or fire.

Quadrat	A device, which is usually a square of polyvinyl chloride tubing, that is placed on the seafloor and used to estimate the density of marine plants or animals in a defined area.
Quadriparesis	Partial quadriplegia.
Quadriplegia	Loss of function, and occasionally sensation, from the neck or chest down.
Radiometer	An instrument, which is essentially a heat flow meter, that is used to detect and measure long wave radiation and solar radiation.
Radular Teeth	Minute teeth that are imbedded in a horny strip on the floor of the mouth of a snail and that are used to scrape up food.
Rebreather	A semi-closed-circuit or closed-circuit breathing apparatus that removes the carbon dioxide exhaled by the diver and adds oxygen as required.
Refraction	The bending of light rays as they pass from one medium to another of different density.
Remotely Operated Vehicle (ROV)	An unmanned, tethered or untethered vehicle that is designed for underwater observation, work, or sample collection.
Repetitive Dive	Any dive conducted within 12 hours of a previous dive.
Repetitive Group Designation	A letter that is used in decompression tables to designate the amount of nitrogen remaining in a diver's body for 12 hours after the completion of a dive.
Residual Air	The amount of air that remains in the lungs after a person voluntarily expels all of the air possible.
Residual Nitrogen	A theoretical concept that describes the amount of nitrogen that remains in a diver's tissues after a hyperbaric exposure.
Residual Nitrogen Time	The time (in minutes) that is added to the actual bottom time when calculating the decompression schedule for a repetitive dive.
Resolution	In photography, the amount of detail (lines per inch) in a photograph.
Respiration	The process by which gases, oxygen, and carbon dioxide are interchanged among the tissues of the body and the atmosphere.
Retinitis Pigmentosa	An inflammation of the retina that involves all layers of the retina.
Rip Current	A strong surface current of short duration that flows seaward from the shore. Rip currents usually appear as a visible band of agitated water; they are generated by the return movement of the water that is piled up on the shore by incoming waves and wind.
Romberg's Sign	A swaying of the body and an inability to stand when the eyes are closed and the feet are placed close together; the presence of this sign indicates neurological impairment.
Round Window	The lower of two membrane-covered openings in the cochlea of the inner ear (*see* Cochlea).
Saturation	A term used in diving to denote a state in which the diver's tissues have absorbed all the nitrogen or other inert gas they can hold at that particular depth. Once saturation has occurred, the amount of decompression time required at the end of the dive does not increase even if the diver spends additional time at that depth.
SCFM	An abbreviation for standard cubic feet per minute; SCFM are commonly used to express the output volume of air compressors.
Scrubber	A component of an atmospheric control system that removes carbon dioxide from the breathing gas by absorbing it with chemical absorbents.
Seborrheic Dermatitis	An inflammatory scaling disease of the scalp, face, and, occasionally, of other areas of the body.

Seismic Waves	Shock waves caused by earthquakes or explosions that travel inside the earth or on its surface.
Seismic Profiling	A method for obtaining a profile of the seafloor or of the layers of sediment and rock below the seafloor; seismic profiling uses a strong energy source from the surface and then measures the strength of the reflected energy.
Semi-Closed-Circuit Breathing System	A self-contained underwater breathing apparatus in which the breathing gas is recirculated through purifying and oxygen-replenishing systems and a portion of the exhaled gas is discharged into the surrounding water.
Sessile	Permanently attached or fixed; not free-moving.
Sextant	A navigational instrument that is used to measure the altitude of celestial bodies.
Shear	A force that lies in the plane of an area or a parallel plane and that tends to cause the plane of an area to slide on the adjacent planes.
Shutter Speed	In photography, the amount of time a camera shutter exposes a film to light.
Side-Scan Sonar	A search system in which acoustic beams are directed laterally and downward in planes perpendicular to the line of the advance of a towed transponder-receiver unit. Return signals are then processed to present a picture of the seafloor on both sides of the towed unit.
Single Lens Reflex (SLR)	A camera that has a movable mirror and a series of prisms that allow the subject to be viewed through the camera's lens.
Solubility Coefficient of Gases	Under the experimental conditions of pressure and temperature, the volume of gas dissolved by a unit volume of solvent.
Sonic Pinger	*See* Pinger.
Sound Pressure	In the presence of a sound wave, the instantaneous pressure at any point in a medium minus the static pressure at that point.
Spectrometer	An instrument used to measure spectra or to determine the wavelengths of various kinds of radiation, from infrared to gamma.
Spectro-radiometer	An instrument used to measure the spectral distribution of radiant energy.
Sphygmoma-nometer	An instrument used to measure blood pressure.
Spina Bifida	A congenital anomaly in which the spinal membranes protrude through a congenital cleft (split) in the lower part of the vertebral column.
Spirit Level	A level that is used in combination with a telescope to compute the difference in elevation between two points.
Squeeze	Deformation of tissue or some portion of the body caused by a difference in pressure.
Stadia	A method of surveying distances that involves the use of two parallel lines to intercept intervals on a calibrated rod; the intervals are proportional to the intervening distance.
Stage Decompression	A decompression procedure involving decompression stops of specific durations at given depths.
Stapedectomy	Removal of the stirrup-shaped bone in the middle ear.
Stipe	The flexible stemlike structure of seaweeds, such as kelp, that serves as the shock absorber between the upper leafy parts of the plant and the anchored holdfast at the bottom.
Stratigraphy	The study of rock strata, and especially of their distribution, deposition, and age.
Strike	In geology, the compass direction that a rockbed would take if it were projected to a horizontal plane on the earth's surface.
Sub-Bottom Profile	*See* Seismic Profiling.

Subcutaneous Emphysema	A condition in which air enters the tissues beneath the skin of the neck and extends along the facial planes from the mediastinum; the presence of subcutaneous emphysema means that air has escaped from the lungs through a rupture of the alveoli.
Substernal	An adjective meaning beneath the breast-bone.
Supersaturated Solution	A solution that holds more gas than would be possible at the same temperature and pressure at equilibrium.
Surface Interval	The period elapsing between the time a diver surfaces from a dive and the time the diver leaves the surface to perform a subsequent dive.
Surficial Maps	Maps showing the two-dimensional character and distribution of material comprising the seafloor of an area.
Synchronization	In photography, the interval between the opening of the shutter and the burst of light from the strobe.
Systole	The rhythmic contraction of the heart that drives the blood through the aorta and pulmonary arteries.
Systolic Blood Pressure	The blood pressure recorded during systole (contraction of the heart).
Talus	The mass of coarse rock fragments that accumulates at the foot of a cliff as a result of weathering and gravity.
Taxa	In taxonomy, a category, such as a species or genus.
Telemetry	The science and technology of the measurement and transmission of data by wire, radio, acoustic, or other means.
Temporal Mandibular Joint (TMJ) Pain	Pain in the area of the temple and the jaws; TMJ pain is often caused by grinding the teeth or by gripping a mouthpiece too firmly.
Thallus	A plant that has a body that is not differentiated into root, stem, or leaf.
Theodolite	An optical instrument used to measure angles and distances.
Thermistor	An electrical resistor made of a material whose resistance varies sharply with temperature in a known manner.
Thermocline	A transition zone of rapid temperature change between contiguous layers of water.
Thoracentesis	A medical procedure involving puncturing of the thorax to remove accumulated fluid.
Thoractomy	Incision of the thorax or chest wall.
Thrombus	A stationary plug or clot in a blood vessel or in one of the cavities of the heart.
Tidal Air	The volume of air inspired and expired by a person during rest.
Tinnitus	A ringing, roaring, or hissing sound in the ears.
Topographic Chart	A chart that graphically represents the exact physical configuration of a place or region.
Torr	A unit of pressure equal to 1/760 of an atmosphere and very nearly equal to the pressure of a column of mercury 1 millimeter high at 0°C (32°F) and standard gravity.
Total Bottom Time	The total amount of time between the time a diver leaves the surface and the time (next whole minute) that the diver begins ascent (in minutes).
Toynbee Maneuver	The act of swallowing while the mouth and nose are closed.
Trachea	That portion of the breathing apparatus that extends from the posterior oropharynx (the posterior portion of the mouth) to the chest cavity.
Tracheobronchitis	Inflammation of the trachea and bronchi.
Transducer	A device capable of being actuated by waves from one or more transmission systems or media, e.g., electrical, mechanical, or acoustical, and of supplying related waves to another transmission system or media.

Transect	In diving, a reference line attached to the seafloor and designed to provide directional orientation or to serve as a base line for scientific observations or surveys.
Transponder	An electronic device consisting of a receiver of signal impulses and a responder that automatically returns signal impulses to the interrogator-responder.
Trigeminal Nerve	The fifth cranial nerve; controls motion and sensation of the face, teeth, and tongue.
Trilateration	A method of determining the relative positions of three or more points and that involves treating these points as vertices of a triangle and then measuring their angles and sides.
Trochlear Nerve	The fourth cranial nerve; controls the superior oblique muscles of the eye.
Turbulent Flow	A type of flow in which the fluid velocity at a fixed point fluctuates with time in a nearly random way; contrasts with laminar flow.
Tympanic Membrane	The thin membranous partition (also called the eardrum) that separates the external ear from the middle ear.
Upwelling	In coastal areas, the replacement of surface waters by deeper waters; upwelling is caused by winds that transport surface waters offshore.
Vagus Nerve	The tenth cranial nerve; controls sensation and motion of the ear, pharynx, larynx, heart, lungs, esophagus, and other parts of the body.
Valsalva Maneuver	The act of attempting to exhale forcefully while the mouth and nose are closed.
Variable-Volume Dry Suit	A type of dry suit that has both an inlet gas valve and an exhaust valve.
Vascular	Consisting of, pertaining to, or provided with vessels; usually refers to blood or lymph vessels.
Vasomotor Control	Regulation of the tension of blood vessel walls.
Vasovagal Effects	A group of physiological effects caused by fright, trauma, pain, and other stress-inducing situations; vasovagal effects include nausea, sweating, paleness, decreased cardiac output, and related symptoms.
Vector	A quantity completely specified by a magnitude and direction.
Ventricle	A small anatomical cavity or chamber, as in the heart or brain. The left ventricle of the heart receives arterial blood and pumps it into the aorta. The right ventricle of the heart receives venous blood and pumps it through the pulmonary artery into the lungs.
Ventricular Fibrillation	A condition in which the ventricles of the heart develop an irregular and chaotic rhythm and the electrical activity of the heart becomes disorganized. If ventricular fibrillation is not stopped immediately, it is fatal.
Venturi Effect	A type of flow in which the flow rate is higher and the relative pressure is lower; venturi effects are caused by a smooth constriction in a pipe or by a restriction of an area through which gas or liquid flows.
Venule	A small vein.
Vertigo	A disoriented state in which the individual perceives himself or herself, or the surroundings, as rotating; vertigo is caused by neurological damage and is sometimes a symptom of serious decompression sickness.
Vestibular Decompression Sickness	Decompression sickness involving the inner ear; inner-ear decompression sickness is often associated with vertigo.
Vestibule of the Ear	The common central cavity of communication between the parts of the internal ear. The vestibule is situated on the inner side of the eardrum, behind the cochlea, and in front of the semicircular canals.
Viewfinder	In photography, a device used to aim the camera.

Virtual Image	An image from which rays of reflected or refracted light appear to diverge, as from an image seen in a plane mirror.
Viscosity	Resistance to flow, a property of fluids.
Vital Capacity	In respiratory physiology, the maximal volume that can be expired after maximal inspiration.
Vortex	A type of flow that involves rotation about an axis, such as occurs in a whirlpool.
Voucher Specimen	A specimen collected to provide species identification or evidence that a given species was collected from a certain place.
Weir	A dam or bulkhead over which water flows, or a bulkhead containing a notch through which water flows; weirs can be used to measure volume in a flow of water.
Wet Submersible	A free-flooding submersible designed so that its occupants are exposed to the ambient environment.
Zooplankton	Drifting marine animals that range in size and complexity from microscopic single-celled animals to large multicellular ones.

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