Getting Clear on the Basics:

The Fundamentals of Technical Diving

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Preface

The aquatic world is one of the most fascinating, exhilarating, and mysterious places on the planet. From an activity pursued only by the most adventurous, to one pursed by the everyday person, SCUBA diving has evolved significantly over the years. There are many ramifications to this kind of change, but in the SCUBA industry, one such ramification is a notable disparity of procedures and practices engaged in by its different members. These variations often go unnoticed; however, on occasion, political conflict and/or loss of life serve to highlight differences in practice and procedures.

The term recreational diving is usually meant to indicate that participants are engaged in simple or uncomplicated diving activity. Activities that involve complex diving such as in deep or overhead conditions are commonly considered "technical." This terminology is inherently ambiguous as it lacks objective markers to ground the distinction. In truth, the principles and skills that make a good technical diver are not fundamentally different from those making any diver a good diver.

The rapidly growing popularity of technical diving has led many people to assume that it has been a commonplace activity for many years. Yet technical diving is in its infancy, and as such is only now beginning to gain widespread acceptance. Ten short years ago, educators were guided largely by intuition, with little in the way of standard practice or experience to help them pilot their way ahead. Today, as educators and individuals in the technical community seek to establish a common ground, what becomes clear is that variations in procedures, ideas, and practices are more the norm here than the exception.

While various groups compete to represent their imagination of how technical diving should be conducted, often mixing into this their belief that technical is a singular form of diving, GUE maintains that a solid diving foundation is not unique to technical diving. What makes technical diving sound is what makes all forms of diving sound: rigorous training, education, and practice. This is the common ground to all forms of diving practice, the fundamental bedrock from which safe and efficient diving practices emerge.

This work is one in a series of GUE works that seek to establish a baseline for fundamental and advanced diving practices. The overriding assumption tying all these together is that there is a baseline of fundamental skills and procedures that promote safe, efficient, and ultimately fun diving.

There are a wide range of written works on the market that offer generic ways to "personalize" diving systems and procedures. Such a perspective might be said to assume that there is no arguably better manner by which to ground various diving practices. At its most extreme, this view presupposes that individuals can be outfitted only with a basic overview and then left to "discover" what works for them. In contrast, this manual, its related cave manual and DIR manual, and complementary future works (training videos, future text, etc.) outline a strategy for approaching all facets of diving activity (training, equipment, nutrition, and health) from a holistic point of view.

This is not to say that divers with a "liberal" interpretation of diving practices will not find this work useful. To be sure, much of the information presented here reflects general concepts that can serve as building blocks toward a coherent conceptual framework. These pieces of information may be discarded, or worked into an existing framework. However, it is my hope that these ideas are taken as a whole, and that the reader will share with me the belief that simple, robust diving practices, coupled with fundamental diving knowledge, beget diving that is safer and more enjoyable. To this end, I wish you the best in your diving and hope that in some small way these works support better safety and more fun within your personal diving.

Safe Diving,

JJ

Chapter 1

Technical Diving : Past and Present

1.0 History

The genesis of diving can be traced back more than 5,000 years, to the commercial exploits of a diver named Scyllis. During the fifth century B.C., the Greek historian Herodotus tells us of the Persian King Xerxes and his attempts to hire Scyllis to recover sunken treasure. Most of these early diving efforts took place in shallow waters, (generally less than 100 feet), and focused on financial or tactical advantage. For example, Alexander the Great (322 B.C.) used divers to remove obstacles in the conquered harbor city of Tyre, (now Lebanon), in order to augment its trading potential. In turn, our need to conduct salvage operations, maintain a military advantage, and engage in aquatic commerce undoubtedly was largely responsible for the continued exploration of the underwater world. Nonetheless, the insatiable thirst for exploring the unknown has contributed to the evolution of diving equally as much.

All of these early dives were limited by the inability to inhale against the pressure of water. At depths as little as three feet, it is essentially impossible to breathe through a tube because of the nearly 200 pounds of pressure that water exerts upon a diver's chest. The first real venture beyond the breath-holding diver's mere minutes of exposure came with the advent of the diving bell, the use of which was documented in the 16th century.[1] These devices trapped air in their interiors and allowed divers to remain below for several hours. In the years that followed, several suit-type modifications of the diving bell emerged; yet, these devices suffered from the same inability to continually provide the diver with fresh air. However, at the turn of the 19th century, diving was to be forever changed. The development of a pump capable of delivering air under pressure to a submerged diver offered divers a constantly replenished air supply. This improvement was incorporated into several styles of diving dress, allowing men much greater freedom. The most popular of these suits was developed by Augustus Siebe, and became known as "Siebe's improved diving dress." This dress is the direct ancestor of the modern day deep-sea diving dress.

1.1 The Mysterious Malady

With the advent of the pump, divers were freed from the limits imposed by the need for fresh air. Divers were now capable of much longer exposures, and diving became much more profitable. In 1840, a unit of the British Royal Engineers employed the new technology to excavate the remains of a sunken warship. With divers often working six to seven hours a day at more than 60 feet, the excavation was successful; yet of all the divers involved, not one escaped a rather mysterious malady described as repeated attacks of rheumatism and cold.

Further advancements in pump capacities allowed even larger chambers to be filled with air, thereby increasing the size and scope of underwater operations. These dry chambers were often used in the

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[1] Edmonds, C., Lowry, C. & Pennefeather, J. (1992) *Diving and Subaquatic Medicine,* p.3. Oxford: Butterworth-Heinemann Ltd.

excavation of bridge footings or in the construction of tunnel sections, and became known by the French word *caisson*, which literally means, "big box." These caissons allowed for long hours of work at depth, and being tremendously effective led to a rapid expansion of their use. In turn, this increased use triggered even more episodes of the baffling sickness mentioned above. Upon their return to the surface, divers were often struck by dizzy spells, sharp joint or abdomenal pain, and difficulty in breathing. The afflicted usually recovered; yet, in many cases, some symptoms were never completely eliminated.

This illness was originally called "caisson disease." Later, the more memorable and descriptive term "bends" was coined during the construction of New York's Brooklyn Bridge. There is some speculation as to the origin of the term. Some think it came from the postures of the stricken divers themselves, but there are others who claim that it came from the fashionable ladies of the day, who affected an awkward, forward-leaning stance known as the Grecian bend. Regardless of the term's origin, this disease, even though it still maintains an air of mystery, has become the best-known danger of diving. We will return to discuss this "malady" later.

1.2 The Birth of SCUBA - Open, Closed and Semi-Closed Systems

It soon became apparent that in many cases it was desirable to have the diver free from a support vessel. This required that the diver be provided with his/her own portable air supply. However, the development of a self-contained breathing apparatus (SCUBA) was delayed by the lack of compressors able to supply sufficient pressure, and by the need for portable cylinders of adequate strength. Thus, several years went by while the requisite technology was developed. Eventually, three types of SCUBA emerged: open circuit, closed circuit, and semi-closed circuit.

The *open circuit system* delivers an air supply directly from a compressed gas cylinder to the diver, who inhales its contents and then vents his/her exhaust directly into the surrounding water. Early *closed circuit rebreathers* used a supply tank of 100 percent oxygen. With this technology, the diver inhaled oxygen and had his/her exhalation routed through a chemical filter that removed the carbon dioxide. Once filtered, oxygen was then added from the supply tank to the breathing loop to replace the portion that was metabolized. This closed system offered both a significant reduction in the gas needed by the diver, and a significant tactical advantage, in that it did not produce bubbles detectable from the surface. However, the limitations of pure oxygen prevented its use below approximately 20 feet, limiting the diver's flexibility. Today, the newer, electronically controlled, closed circuit systems, or "rebreathers", can use multiple gasses, and therefore provide great flexibility in their operational depths. The *semi-closed circuit units* also recycle gas, but purge some of the exhaled quantity to the surrounding water. Closed circuit systems (semi- and fully-closed) provide much greater use out of a given supply than do open circuit systems. Efficient rebreathers allow four to thirty times the gas duration of conventional open circuits. Fully-closed rebreathers provide much longer duration than either semi-closed or open circuit systems, but with greatly increased complexity. Semi-closed units do produce some bubbles, but are generally less complex than closed systems, and, therefore, seemingly less prone to failure.

Given early equipment limitations, it was natural for individuals to investigate rebreather systems, and for many years to come they would seek the benefits of recycled gas supplies. However, by 1866, the first technological limitation of a self-contained apparatus was overcome. Benoist Rouquayrol patented the first demand-regulator, which adjusted the flow of air from a supply tank to meet the demands of the diver. While the lack of a supply tank of sufficient strength still prevented open circuit from becoming a practical reality, the demand regulator technology gave rise to the first commercially practical closed circuit system. In 1878, H.A. Fleuss developed the first SCUBA unit using a supply cylinder of 100 percent oxygen. Because the system used 100 percent oxygen, significantly lower pressure was necessary than was needed with air systems that supplied only 21 percent oxygen.

The flexibility of this SCUBA unit rapidly gained popularity with the military, and by World War I was the basis of submarine escape equipment in the Royal Navy. But it was two Frenchmen who were to forever change the world of SCUBA. In the 1940's, Captain Jacques-Yves Cousteau and Emile Gagnan combined improved demand-regulators with high-pressure cylinders to create the first truly viable open circuit system, the "Aqua-Lung." With few modifications, this system still represents today's most popular diving equipment, and has been largely responsible for opening the underwater world to millions of divers. Many variations of the SCUBA apparatus were developed in the following years, but it was Cousteau and his newly-developed Aqua-Lung that would make SCUBA prominent.

Following their discovery, Cousteau and Gagnan continued to develop new diving techniques as they explored and photographed wrecks, and though Cousteau is largely to be credited with making recreational SCUBA possible, his path took a different course than the one taken by recreational SCUBA. Cousteau can easily be called the first "tech diver"; one who spent a lifetime exploring all manner of environments, from cave and ice to deep ocean and wreck. His feats filled millions of people with fascination and excitement, and would encourage them to explore the underwater world.

The earliest years of recreational SCUBA training were rigorous and labeled too militaristic by some educators. They argued that easier training would open diving to a greater portion of the public, and make it more popular and profitable. This encouraged some SCUBA manufacturers, who needed a growing diving population to support their products, to actually develop a number of the earliest diver training courses. This led to the growth of the recreational diving public, which, coupled with the establishment of private training organizations like PADI, succeeded in bringing SCUBA home to everyone. With the growth of these organizations came the perception that nearly anyone could go SCUBA diving, a perception that augmented both recreational diving and its potential as a profitable business.

As SCUBA training became more accepted, and more people explored the underwater world unencumbered by surface-supplied air hoses and heavy diving dress, the sport became a business. Now its administrators would spend decades trying to balance its growth and popularity with quality and safety.

1.3 The Birth of Technical Diving

Cousteau traveled the world filming, studying, and playing in some of the world's most beautiful underwater locations; these early adventures undoubtedly encouraged the growth of recreational diving. Ironically, it was also Cousteau who could most easily be considered the world's first technical diver. While recreational organizations were quick to seize upon the potential for enjoyment and the marketability of shallow "sport" diving, few imagined a future in which the average diver might consider diving in the areas or to the depths explored by Cousteau.

In 1946, Cousteau and his team attempted to explore the famous inland cave, Fountain de Vaucluse. The dive nearly cost Cousteau his life as he was besieged by numerous problems. Poor planning, ineffective communication, narcosis, and carbon monoxide poisoning were but some of the many difficulties he encountered. Recounting this incident, he claimed it was the "worst experience to befall us in five thousand dives . . ." Though the divers narrowly escaped with their lives, the attempt to dive the Fountain de Vaucluse marks a significant date in the history of cave diving, as the Aqua-Lung and the freedom it allowed opened new avenues of exploration. Technical diving was off to an auspicious beginning.

Technical diving can be described as an activity undertaken beyond the limits of recreational diving, one that historically has been pursued by military and scientific divers. However, Cousteau, along with some of the early pioneers in SCUBA, forever established the spirit of technical diving. Today, nearly 40 years after some of Cousteau's early explorations, several new training agencies have begun to certify divers in what has become officially known as technical diving.

The fact that no formal training in the use of SCUBA existed mattered little to the early explorers. In fact, as early as 1953, the Florida Speleological Society (a branch of the National Speleological Society) established the first cave diver training curriculum. This program began teaching cave diving techniques several years before the genesis of early open water agencies, such as the Los Angles County Scuba Program, and well before the emergence of conglomerates, such as the Professional Association of Dive Instructors (PADI). The 1950's saw roughly 3,000 divers per year venturing into the caverns and caves of Florida. During this time, early cave divers explored about 5,000 feet of cave passages, along with countless wrecks and deep ocean areas. Yet it was not until 1985 that the early technical diving agencies began to certify divers.

1.3.1 What is Technical Diving?

The term *technical diving* refers to diving that is neither commercial in nature (i.e. without pay) nor military in application. In some ways, the formulation "technical diving" resists easy description; a number of divers assert that dives using gasses other than air are technical, while others insist that deep and/or complex dive plans are technical dives. In truth, the lines demarcating the field of technical diving are blurred; precise definition is arbitrary and pointless. Commercial and military diving are distinct activities in which superiors require mission-specific activities generally beyond the control of the diving team. Recreational or sport diving is usually for fun, but divers would do well to learn from the precision of military and scientific operations, particularly as the recreational activities become more risky.

Calling a form of diving "technical" arbitrarily attempts to outline a different level of diving risk when that risk does not actually exist. Diving risk is part of a continuum, and technical divers are not necessarily more at risk than recreational divers. As depth and task-loading increase, divers must be better prepared, with more experience and proper training to handle the risks. But there is little risk if one is trained to deal with the task at hand. What this means is that risk should be understood in terms of attitude, experience, and training, not in terms of the type of diving. Too many individuals view diver training as a list of accomplishments that should be checked off as quickly as possible. Unfortunately, diving educators sometimes encourage this perspective. In truth, training is what supports individuals in being able to safely pursue diving. Diving is actually where individual emphasis should lie.

Generally speaking, technical diving has not been proven to be inordinately more dangerous than recreational diving, and insurance organizations have been willing to insure most forms of technical diving. Early predictions that technical divers would expose organizations to substantial liability have not been realized. Therefore, technical diving now enjoys things that seemed nearly inconceivable in the early 1990's: a growing market share, profitability, and liability protection.

1.3.2 The Fate of Technical Diving

Change can come so quickly that sometimes it can go unnoticed. Not too long ago, groups like PADI marshaled to ban technical diving from the SCUBA industry's largest annual trade show. Today, these same organizations are proud to embrace technical diving with a new-found fervor. The motivations behind this change of heart are unclear. If they are financial in nature, then it is uncertain whether this change of heart is consistent with the best interests of those involved in technical diving.

As a market, technical diving has now become commercially viable; the growth of companies and services catering to the interests of technical diving attests to that. This is evident also by the attempts made by solidly recreational manufacturers to make inroads into the technical diving market. Nonetheless, manufacturers of SCUBA equipment are not the only ones seeking to capitalize on this new and growing market; open water training agencies seek to do so as well.

Initially, one might assume that this change is for the better, that by bringing their financial might and varied resources to bear on the technical diving market (e.g. by helping to create new training materials as well as a much larger market), open water agencies will help promote the interests of technical divers. That is debatable. Not only are those agencies' motives for entering a domain against which they fought for years questionable, but so is their competence to teach technical diving.

Surely the standards by which one might evaluate the qualifications of individuals or organizations to train divers are fraught with personal opinions and bias. However, diving in general, and more particularly technical diving, is a self-regulated activity that allows business entities to regulate, and thereby limit, their own industry. It follows, then, that these same entities will favor relaxing diving standards in order to stimulate the growth of their consumer base. In turn, these relaxed standards translate into less-competent divers. Today, easier courses and more "streamlined" training are the rule rather than the exception in the open water market. Courses are becoming shorter and less academically robust every year.

Diving on a calm day in warm water on a 30-foot reef is not likely to involve many difficulties. This perception has revolutionized novice training; today, students are only given the most minimal training before they are allowed to begin diving. Some groups have even gone so far as to eliminate from their training curricula many of what, in the past, were considered fundamental diving skills. Though this kind of training, and the underlying philosophy supporting it, may work well for recreational diving, it does not work for technical diving. Many diving educators argue that, because of the brevity of their training, new recreational divers are becoming less capable and less comfortable each year, thereby making them poor candidates for technical training. It is unlikely, then, that recreational diving organizations will be able to produce competent technical divers, when said agencies are having difficulties producing divers who qualify as viable technical diving candidates. This raises serious questions regarding the competency of open water agencies to branch into technical diver training. Even though what makes a student a "qualified" open water diver is debatable, what is not is that competent technical diving is not supported by such training practices.

Few would blame a business for making choices that would make that business more profitable. However, SCUBA diving in general, and technical diving in particular, are different from most other activities in that the quality of one's training directly impacts on one's likelihood of survival. Whereas most recreational activities penalize mistakes and accidents with sprained ankles and broken bones, SCUBA diving penalties can easily be much more severe. This, coupled with the greater demands imposed on one by technical diving, forces one to question whether this expansion in technical training serves the best interest of technical divers. It is not inherently wrong for companies to seek profitability. Divers are actually rewarded by the growth and expansion of successful diving companies. However, this profitability cannot be sought at the expense of training proficiency or diver safety. In the end, it is the student who has the most control over the type of training he or she receives. Individuals seeking bargain training usually get exactly the kind of training for which they pay.

1.4 How Can Divers Receive a Good Education?

Choosing among the many promises made by agencies and individuals seems like a daunting task. Each one's claim to be the best or of the highest quality seems to blend together, leaving potential students to make a sometimes difficult choice. In light of this, a sensible course of action here is to evaluate the instructor and agency.

What is the instructor's personal diving history?

Unfortunately, there seems to be a growing number of instructors who teach activities in which they are inexperienced. It is all too common for instructors to claim dozens or hundreds of dives as proof of experience. However, these dives (if true) are mainly teaching dives that are neither personally demanding nor helpful for evaluating the suitability of the instructor. As this is the best way for students to assess pertinent information, be sure that the instructor does the kind of diving for which one is considering training, and be sure that such diving is done on the instructor's own time.

How often does the instructor teach and/or dive?

While there are some very good instructors who teach on a part-time basis, students should strive to get a feel for the time these individuals spend in the water. Instructors with regular jobs have one unique benefit in that they may be less caught up in the business of certification and be more inclined to focus on quality instruction. The downside with these instructors, however, is that a "normal" job, along with teaching and daily fitness routines, leaves precious little time for the personal dives that will make them a good source of information. Conversely, instructors that do not dive recreationally are not taxing their own ability and are not accumulating the experience that allows them to relay valuable information.

Does the instructor take his/her role seriously?

Instructors who lack the dedication to remain current with new developments, or who fail to maintain high levels of training and fitness, are unlikely to be very efficient educators. Maintaining a quality educational presence is about much more than the original investment of instructor training. It involves committing oneself to personal diving, academic review, and regular fitness training. Unfortunately, some educators fail to realize this.

Educate yourself.

The tricky used car salesman might say that few things are more frustrating than an educated consumer. If one is are educated, one is more likely to be able to evaluate an instructor's strengths and weaknesses, and more competent to ask questions in areas where what is presented conflicts with what one knows. Regardless of the instructor's ability, one will benefit greatly from a strong period of pre-course study.

Don't be fooled by the discount structure.

Nearly everyone knows that, in the grand scheme of things, they get what they pay for. However, this knowledge rarely keeps people from trying to get more for less. In the case of instruction, educators who discount their training, or who play pricing games, either do not value their time, or they sell a less-than-optimal service. It is ironic that people will spend thousands of dollars on equipment and travel, but will try to save a couple hundred dollars on an education that could save their lives.

Does the agency matter?

The most common way of finding a qualified educator is to ask friends and associates. While this is typically a sound method, it fails to address whether differences in agencies should impact the selection process. After all, is not the *raison d'etre* of an organization a claim to better training? Why, then, would most people contend that distinguishing between agencies is of little value? Actually, most training is fairly similar, with requirements that are often barely distinguishable. Furthermore, most active instructors teach for a number of agencies simply to avail themselves of different student preferences. Nonetheless, the agency does matter;

and should be evaluated on the same grounds as the individual instructor. One should ask, to what degree does the agency strive to insure diving safety, experience, currency, fitness, and professionalism in its educators.

1.4.1 Global Underwater Explorers: Why Another Agency?

The perceived decline in educational excellence, coupled with a rejection of the conventionally supported risk of deep air diving, has led numerous diving leaders to marshal their support behind a new educational effort. Global Underwater Explorers is a new organization founded by leading educators, scientists, and explorers to redefine the nature of aquatic education. Unlike conventional training organizations which support their efforts by training divers, GUE is a broad-based, non-profit organization with a wide range of international research and exploration initiatives. Not only does this free the agency from the financial restraints imposed on other organizations, but this wide educational base also allows students and fellow educators access to an unprecedented educational resource.

1.5 Self-Assessment

The single greatest safety factor in open water recreational diving is that, no matter what happens, (equipment malfunction, loss of breathing gas supply, loss of buddy, etc.), divers can always make an independent, controlled, emergency swimming ascent (ESA) to the surface. Two factors make this possible:

1. Open water divers who remain within the recommended depth limits for recreational diving are usually less than 100 feet/30 meters from the surface, and never more than 130 feet/40 meters. Emergency swimming ascents would be significantly more difficult if recreational divers ventured farther from the surface or entered overhead areas.

2. With the exception of certain recreational-level specialty diving activities, open water divers are never under overhead obstructions that would prevent them from making an immediate and direct ascent to the surface.

Obviously, any time divers place a barrier between themselves and the surface, they compromise their ability to make controlled emergency swimming ascents. Thus, by entering overhead environments, incurring decompression obligations, or venturing deeper into the water column, divers deprive themselves of recreational diving's greatest safety factor, the *controlled emergency swimming ascent*.

Divers choosing to engage in these more advanced technical dives must prepare themselves by securing the proper training, developing a clear awareness of their equipment, and cultivating higher levels of personal fitness. While casual recreational diving may be an activity suitable for everyone, safe technical diving is not; it is limited to those who are willing to commit themselves to more extensive levels of preparation.

1.5.1 Readiness for Advanced Diver Training

Many experts estimate that less than one percent of the recreational diving population possesses the knowledge, skills, attitude, and judgment needed to be as safe as necessary in demanding environments such as caves. Most divers are not willing to invest the required energy to develop the skills that are crucial for success in more aggressive diving environments. One must be honest with oneself when deciding to which group one belongs. Other than Advanced Diver certification, there are few commonly recognized prerequisites for enrolling in technical diver training. Nonetheless, students who are successful in more rigorous training curriculums typically share the following attributes:

Experience

Ability

Fitness

1.5.2 What Level of Experience Should One Achieve Before Taking a Technical Diving Course?

Divers with more experience best manage the rigorous demands of certain environments. Divers not yet adept at fundamental skills often find the burden of aggressive environments overly taxing. A significant number of students who participate successfully in technical diver training are divemasters or instructors, or individuals with comparable leadership-level training. None of the training for these levels of certification is necessarily relevant to the curriculum at hand; it is simply that those students who successfully complete this type of training have a high level of commitment to diving. However, the dedication and awareness of many leadership divers may be found in individuals from all ranks.

Career Total: For entry levels of technical training, successful course participants have usually logged at least 100 scuba dives over the past 48 months; in more advanced levels, successful participants have usually logged several hundred successful dives.

Recent Experience: Successful students typically log at least 10 to 20 dives in the six months prior to the inception of their technical diver training.

1.5.3 What Buoyancy Skills Should One Master Before Taking a Technical Diving Course?

Students who succeed in technical diver training typically practice and master the buoyancy skills outlined on this page, in confined or open water, within 30 days of the start of the course.

Weighting: Prospective students should be able to weight themselves so that, at the end of a dive, with 500psi (35bar) in their tanks, they can hover motionless at safety-stop depth, with no air in their BC's.

Body Position: By shifting tank and weight system height, students should be able to position themselves in a perfectly horizontal hover. Students can test this by seeing if they can view everything that is going on behind them simply by tucking their chins to their chests.

Helicopter Turn: While in a horizontal hover, students should be able to complete a 360-degree turn, simply by sculling with ankles and fins. The rest of the body should remain motionless throughout the turn (especially the hands).

1.5.4 How Important is Physical Fitness to the Technical Diver?

Technical diving is a physically demanding activity. In an emergency, personal fitness can literally make the difference between life and death. Furthermore, fitness is also a key factor in reducing the risk of decompression illness. Successful technical divers typically have the following commitments to personal health and fitness:

Diet/Body Mass: During a typical day, they have a fairly good sense of their total caloric intake, as well as their ingested ratio of proteins, carbohydrates, and fats. Fatty foods, found at most fast-food restaurants, are simply not part of their normal diet. Successful technical divers have little difficulty maintaining a body weight that is in proportion to their height, sex, and build. Their percentage of body fat, relative to total body mass, is well below that of the typical recreational diver.

Exercise: A technical diver's minimum aerobic workout should consist of at least 20 minutes a day, three times a week. At least 30 minutes every day is better. In general, exercise is something successful technical divers make time for, not something they do when they have time.

Lifestyle: Smoking tobacco, substance abuse, and late night partying are all inconsistent with successful technical diving. If one is committed to any of these, one should pursue another recreational activity.

Medical Exam: One should either be able to answer every question on the RSTC Medical History/Exam Form with an unqualified "No", or have a signed physician's approval for diving, based on physical exam that meets RSTC/UHMS guidelines, which took place within the last twelve months.

1.5.5 Are You Qualified?

How do you stack up against the criteria just presented? If you can honestly say, "Yes, that's me," you may be ready for the more demanding world of technical training. If you meet some of the criteria outlined, but not all of them, you should reconsider technical diving or consult a professional to determine how best to prepare for technical training. If, however, you find yourself coming up short in more than just one or two of the above categories, technical diving may not be for you. Though assertions of this sort are not what people want to hear, in the end, they speak to the best interests of those involved.

Technical diving does not have to be any more dangerous than other forms of diving. The risks assumed on a particular dive are largely a matter of individual choice, and divers must make some of these choices well before entering the water. As a responsible organization, GUE encourages divers to base their decisions on an honest, thorough evaluation.

Chapter 2

Introduction To Nitrox

2.0 Why Add Oxygen to Air?

The idea behind Nitrox is not so much to add oxygen, but to reduce nitrogen. As is commonly known in the diving world, nitrogen is what really limits our diving. By increasing the amount of oxygen in our mix, we correspondingly reduce the amount of nitrogen in our mix. A 32% Nitrox mixture, for example, increases the percentage of oxygen from 21% (normally found in air) to 32%, thereby reducing the percentage of nitrogen from 78% (normally found in air) to 68%. With less nitrogen in the breathing mix, the diver can enjoy longer bottom times with a potentially reduced risk of decompression sickness.

2.1 What is Nitrox?

Information about Nitrox can be broken down into the following facts:

Nitrox is technically any mixture of nitrogen and oxygen, but more commonly considered to be an oxygen-enriched mixture.

Oxygen-enriched air has been actively used for more than 30 years, and has existed as a concept for more than 200 years.

Manipulating oxygen levels was essential to certain military operations, and became common in commercial, scientific, and medical fields as early as World War II.

The National Oceanic and Atmospheric Association (NOAA) released the first publicly available Nitrox tables in 1979, fueling the use of Nitrox in the recreational communities.

Nitrox gained significant recreational popularity in the early 1990's.

Other terms for oxygen-enriched air include Safe Air and Enriched Air.

2.2 Nitrox History

The concept and use of oxygen-enriched air mixtures is over 200 years old. The technology has been used on thousands of dives with an impressive safety record. The following are highlights of the history of Nitrox.

1773: English chemist Joseph Priestly discovers oxygen. Shortly thereafter, the French chemist Antoine Lavoisier determines that oxygen is vital to life.

1794: English physician Reddoes establishes breathing oxygen-enriched air as a medical procedure.

1874: Paul Bert prepares breathing mixtures containing 40 percent and 70 percent oxygen to be used by balloonists to survive the hypoxia associated with their ascensions.

1878: Paul Bert publishes the results of some 670 experiments with oxygen-enriched atmospheres using a hyperbaric chamber, and proposes that CNS toxicity is a function of oxygen concentration.

1879: First documented dive using oxygen-enriched air by Henry Fleuss. The dive is on a breathing mixture estimated to be between 50% and 60% oxygen.

1912: Robert Davis and Leonard Hill, under the direction of J. S. Haldane, develop a self-contained rigid diving helmet, utilizing 50% oxygen-nitrogen breathing gas with operating depths to 100fsw. Users are amazed at the decompression advantages of this apparatus.

1913: Draegerwerk produces a self-mixing diving dress that automatically mixes nitrogen and oxygen supplies to a 60% oxygen content. This would be the forerunner of modern-day rebreathers.

1942: The adverse effects of high partial pressures of oxygen are becoming documented, and it is established that concentrations greater than 2.0 atmospheres absolute could not be tolerated for an extended period of time.

1942: Royal Navy Commandos routinely use breathing mixtures of 32.5%, 40% and 60% oxygen in closed circuit breathing apparatus, reducing decompression and the risk of oxygen toxicity.

1955: Dwyer calculates Nitrox tables for the U. S. Navy EDU and the Navy begins to use these mixes to lower decompression obligations significantly.

1965: Workman publishes decompression schedules for nitrogen-oxygen and helium-oxygen breathing gasses.

1970: Dr. Morgan Wells, Diving Officer for NOAA, begins instituting diving procedures for oxygen-enriched air.

1978: NOAA publishes operational procedures for a standard mixture of 68% nitrogen, 32% oxygen, known as NOAA Nitrox I. Soon after, procedures for a mixture of 64% nitrogen, 36% oxygen, known as NOAA Nitrox II, would be established.

1985: Dick Rutkowski brings NOAA diving technology to the recreational diver by forming the International Association of Nitrox Divers (IAND) in Key Largo, Florida. At about the same time, Ed Bettes forms American Nitrox Diving, Inc. (ANDI) to support the Northeast diving community.

1987: Members of the Woodville Karst Plain Project (WKPP) begin to accelerate the use of mixed gasses in the deep cave explorations of Tallahassee, Florida. This deep cave exploration pioneers the regular use of mixed gasses in technical diving.

Their cooperation with the international research, education and exploration activities of Global Underwater Explorers (GUE), formed by some of the WKPP's founding members, vastly expands the WKPP's groundbreaking activities.

GUE combines research and exploratory skills and procedures with an international focus on education to form the world's most unique aquatic organization.

2.3 Advantages to Breathing Nitrox

There are many advantages to breathing Nitrox. These include the following:

Bottom time and/or decompression obligation is related to the accumulation of metabolically inert gasses (such as nitrogen). Since Nitrox reduces the percentages of metabolically inert gasses in the diver's breathing mixture, it can significantly impact bottom time and/or decompression.

Less nitrogen in the diver's breathing mix allows for longer bottom times and safer dives. For example, a 60ft (18m) Nitrox dive can last for 100 minutes as compared to 60 minutes on air.

Custom Nitrox mixtures allow divers to maximize their bottom time while reducing the risk of decompression sickness.

With Nitrox, divers can choose longer dives and/or or shorter decompression obligations with reduced decompression stress.

FIGURE 2.1 – NO DECOMPRESSION LIMITS WITH AIR AND NITROX

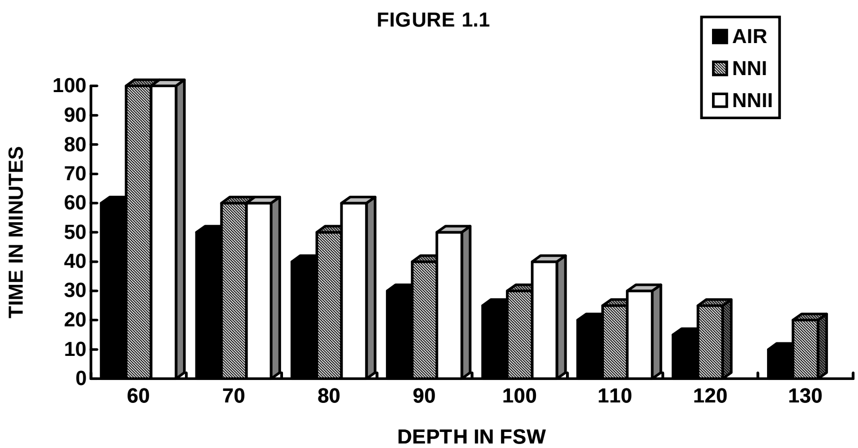

TABLE 2 .2 NO DECOMPRESSION LIMITS WITH AIR AND NITROX

DEPTH (FSW)	AIR 21%	32%	36%
60	60	100	100
70	50	60	60
80	40	50	60
90	30	40	50
100	25	30	40
110	20	25	30
120	10	25	*
130	10	20	*

TABLE 2.3 EQUIVALENT AIR DEPTHS WITH AIR AND NITROX

DEPTH (FSW)	AIR 21%	32%	36%
50	50	38	34
55	55	43	38
60	60	47	42
65	65	51	46
70	70	56	50
75	75	60	54
80	80	64	59
85	85	69	63
90	90	73	67
95	95	77	71
100	100	81	75

2.4 Complications of Using Nitrox

Our understanding of Nitrox is based on both scientific research and empirical evidence. Of course, the use of Nitrox is not without risk. Nitrox diving, like air diving, has certain risks and limitations.

Nitrox does not eliminate the risk of decompression sickness. Divers who take full advantage of its longer bottom times will not likely reduce their DCS risk to a great degree.

When divers do not respect the established time and depth limitations of Nitrox, CNS oxygen toxicity can result in underwater seizure and drowning.

Very aggressive diving profiles may overextend the margin of safety with Nitrox.

Very extensive (very long and/or frequent) enriched-air exposures have the potential to initiate lung damage, leading to pulmonary toxicity. *Unlikely in recreational use.*

Similar (theoretically greater) narcosis potential exists as compared to air.

Oxygen Toxicity: The single biggest hazard to the user of Nitrox is Oxygen Toxicity, more specifically Central Nervous System Oxygen Toxicity (also known as CNS toxicity). Though oxygen is required to sustain life, too much oxygen can cause damage, even death. Damage to the pulmonary system is possible with extensive exposures to oxygen-enriched mixtures. Generally speaking, the risk to the well-informed and responsible technical diver is negligible.

These limits are commonly accepted standards, made public by the National Oceanic Atmospheric Association (NOAA). The development of these limitations emerged out of thousands of exposures, some of which are chronicled in this manual. (Kenneth Donald's Oxygen and the Diver is an excellent historical representation of these studies; unfortunately, it is now out of print.)

A PO_2 of 1.4 is the maximum recommended for a diver under any stress, while a PO_2 of 1.6 is the upper limit usually reserved for a resting diver during decompression. Nonetheless, these limits will vary relative to the factors increasing oxygen susceptibility, i.e. the diver's exertion

TABLE 2.4 CNS TOXICITY LIMITS FOR DIVING EXPOSURES

PO_2	Single Exposure (Min.)	Maximum (24-Hour Day)
1.4	150	180
1.3	180	210
1.2	210	240
1.1	240	270
1.0	300	300
0.9	360	360
0.8	450	450
0.7	570	570
0.6	720	720

TABLE 2.5 CNS TOXICITY LIMITS FOR DECOMPRESSION MIXTURES

PO_2	Single Exposure (Min.)	Maximum (24-Hour Day)
1.6	45	150
1.5	120	180

level, ambient water temperature, exposure time, and personal physical condition.

Decompression Sickness: Generally speaking, nitrogen absorption limits the time a recreational diver can stay submerged. Although Nitrox mixtures will have a lower amount of nitrogen than air, nitrogen will still be a major part of the gas. 'No Decompression Limits', although extended, are inescapable parts of Nitrox diving. If the No Decompression Limits of Nitrox are exceeded, one's odds of getting "bent" are similar to those when using air.

Narcosis: Historically, divers have been told that Nitrox will reduce narcosis levels. To be sure, Nitrox mixtures reduce nitrogen content, seemingly making divers less susceptible to narcosis. However, a number of gasses display narcotic properties. The properties that induce narcosis are similar in oxygen and nitrogen. This leads many to conclude that the risk of narcosis is the same or greater for the Nitrox diver as for the air diver. Responsible divers assume greater narcosis and adjust accordingly, often by diving shallower and/or using helium mixes in most of their diving.

Diver Error: As with air diving, the greatest risk to a diver's safety is often the manner in which s/he conducts his/her diving. Individuals with careless attitudes put themselves at greater risk than those who are mindful of detail. This is particularly true with more advanced diving. Careless individuals have no place under water because they place themselves and their diving team in great danger. This is equally true in one's use of Nitrox. Careless use can trigger terrible consequences.

Miscellaneous: As with air, Nitrox can also be the source of a range of barotraumas (pressure induced injuries) and should never be thought of as a miracle gas.

2.5 Looking into the Future

This is an exciting time to be a diver. The 1980's saw a boom in the number of certified divers. Many of those, as well as newer divers, are now ready for currently emerging technologies. A few advances are rapidly becoming part of mainstream diving.

Nitrox has become very common, and is often recognized as the gas of choice for shallow diving activities. Meanwhile, many divers have seized upon helium-enriched gasses as a standard mixture for dives in all depth ranges.

Helium-enriched diving is rapidly becoming the standard for dives in the 0ft to 400ft (0 to 125m) depth range. Hyperoxic Trimix or "Triox" (enriched-oxygen Trimix) is commonly used from 0ft to 150ft (0m to45m) due to its improved physiological comfort, elimination of narcosis, and reduction of breathing resistance.

Computer software (such as GUE's DecoPlanner) is allowing divers to generate their own diving tables with a variety of mixtures and diving depths.

Rebreathers (devices that remove carbon dioxide from the diver's exhaust) were at one time very rare in all but a handful of military teams. Today rebreathers are growing in popularity with non-military divers.

In short, while Nitrox has all but eliminated the need for air diving shallower than 100ft (30m), divers reaching to deeper depths can enjoy the great benefits and safety of helium-enriched diving. What this means is that air diving is becoming a curious historical footnote as divers continue to appreciate the advantages of proper mixtures. Indeed, many experienced divers have trouble remembering the last time they used air as a diving mixture, choosing instead to take advantage of the amazing flexibility of Nitrox and helium-based diving.

Chapter 3

Diving Physics Made Simple

3.0 Introduction

Physics is a science that describes the relationship between matter and energy and postulates the laws that govern their interaction. At its more esoteric level, physics involves describing the seemingly chaotic interactions of subatomic particles, and can be very complicated. However, physical interactions that are immediately relevant to diving are relatively simple. Nonetheless, the reader should be aware that in what follows the discussion of certain physical interactions is simplified for purposes of description and analysis. For example, we commonly treat the interaction of various gasses as a predictable linear function. In other words, we imagine that each additional 100psi (6.8 bar) is the same amount of gas at any pressure in our cylinder. In reality, however, this quantity becomes less as the tank fills with gas. Beyond the tank's rated pressure, molecular action increases the measured pressure with less actual gas supply. These *ideal* gas laws (as opposed to *real* gas laws) are an example of the manner in which we simplify "reality" for the ease of measurement. Later sections of this manual will deal with this and other over-simplifications. In general, this section will treat simple and practical aspects of gas interaction and mixing.

3.1 Basic Review of Gas Laws

A basic review of Charles' Gas Law, Boyle's Law, Dalton's Law, Henry's Law and the Oxygen Window follows.

3.1.1 Charles' Gas Law

Defined: Pressure and temperature are directly related. Therefore, as temperature decreases so does available pressure.

Formulas: Assume either Pressure or Volume is constant

If P is constant then $V1/T1 = V2/T2$[1] *(3.1)*

If V is constant then $P1/T1 = P2/T2$ *(3.2)*

This law is important when filling cylinders, because given that the internal volume is constant, as the temperature rises, so does the pressure. Imagine, then, leaving SCUBA cylinders in a vehicle on hot days; as the temperature increases, so does the pressure. Correlatively, as the temperature decreases, so does the available pressure, equating to less usable gas volume.

1-T must be in absolute units, Rankin or Kelvin

3.1.2 Boyle's Law

Defined: Pressure and volume are inversely proportional. Therefore, as we descend, the total pressure increases while the volume decreases, as shown in table 5.0 below.

Formula:

$$P = 1/V \qquad (3.3)$$

TABLE 3.1 PRESSURE VOLUME RELATIONSHIP

Depth	Pressure in ATA	Pressure in PSI/Bar	Volume
0' (0m)	1 ATA's	14.7 psi (1 bar)	1 cft (cubic meter)
33' (10m)	2 ATA's	29.4 psi (2 bar)	½ cft (cubic meter)
66' (20m)	3 ATA's	44.1 psi (3 bar)	1/3 cft (cubic meter)

3.1.3 Dalton's Law

Defined: The pressure exerted by each individual gas within a mixture of gasses is the partial pressure.

Formula:

Pt = Pn + Po + Pother, also commonly known as Pt= P1+P2+P3 . . .

(3.4)

Consider the following examples while breathing an air mixture:

At surface: O_2= .21bar (3.09psi), N_2= .78bar (11.61psi) or a total 14.7psi / 1bar at 1 ATA

At 33 feet: O_2=.42bar (6.2psi), N_2= 1.58bar (23.2psi) or a total 29.4psi / 2bar at 2 ATA

At 66 feet: O_2=.63bar (9.3psi), N_2=2.37bar (34.83psi) or a total 44.1psi / 3bar at 3 ATA

3.1.4 Henry's Law

Defined: Henry's law describes the solubility of gasses in liquids.

Example: If the ambient pressure (P) increases (descent), inert gasses, such as nitrogen, are diffused into liquid (on-gas), because a gradient develops between the PPNa (Partial Pressure of Nitrogen in the ambient gas) and the PPNliq (Partial Pressure of nitrogen in the liquid). If PPNa > PPNliq, then N diffuses into the liquid.

If the ambient pressure (P) decreases (ascent), inert gasses, like nitrogen, are released from the liquid (off-gas), because a gradient develops between the PPNa (Partial Pressure of nitrogen in the ambient gas) and the PPNliq (Partial Pressure of nitrogen in the liquid). If PPNa < PPNliq, then N is released from the liquid.

3.1.5 Oxygen Window Summary

Pn = partial pressure of arterial nitrogen

Pio = partial pressure of inspired oxygen

TABLE 3.2 PARTIAL PRESSURES OF AIR AT VARIOUS DEPTHS

FSW Depth	Pressure in ATA	Pressure in PSI/Bar	Nitrogen	Oxygen
0' (0m)	1 ATA's	14.7 psi (1 bar)	11.61 psi	3.09 psi
33' (10m)	2 ATA's	29.4 psi 2 bar)	23.2 psi	6.20 psi
66' (20m)	3 ATA's	44.1 psi (3 bar)	34.84 psi	9.30 psi

TABLE 3.3 BREATHING 100% OXYGEN AT VARIOUS DEPTHS

Depth	Pressure	Volume	Bubbles	Blood	Bubble and Blood Gradient
0 ft (0 m)	1 ATA	1 cft	Pn =1V= 1	Pn = 0 Pio2 = 1	Pn=1 vs. Pn=0
33 ft (10 m)	2 ATA	½ cft	Pn = 2V= ½	Pn = 0 Pio2 = 2	Pn=2 vs. Pn= 0 Better Gradient = Better Diffusion
66 ft (20m)	3 ATA	1/3 cft	Pn =3V = 1/3	Pn = 0 Pio2 = 3	Pn=3 vs. Pn= 0 Better Gradient = Better Diffusion

V = volume of bubble (theoretical size of bubble)

Resulting General Gas Law:

$(P1\ V1)/\ T1 = (P2\ V2)/T2$ *(3.5)*

(with T in absolute units, R or K)

3.2 Nitrox Parameters

Nitrox calculations are not particularly complicated, nonetheless, it is important to understand the basic procedure for calculating gas mixtures. In much the same way as calculators exist to simplify mathematical analysis, charts exist to simplify the mixing of Nitrox. While most divers are unlikely to mix their own Nitrox, having a basic understanding of how to do this ensures that they can locate a reputable facility and remain within safe limits.

3.2.1 The Big Three

When one uses Nitrox, one is usually faced with three variables:

How **deep** can one go (depth in ATA's)?

What **mix** is best for the proposed dive (mix, in decimal form)?

What **PO_2** will the body be exposed to (PO_2 in ATA's)?

Given any of the above two variables, one can always find the third. The calculations required to find these variables are easily represented by a simple formula called the *T formula*. Below is an illustration of how it works.

T Formula:

$$\frac{PG\ (PO_2)}{FG\ (\%) \times D\ (ATA)} \qquad (3.6)$$

Where:

PG= Pressure of the gas (in this case the pressure of oxygen (PO_2))

FG= Fraction of the gas (with the percentage of a gas represented as a fraction)

D= Total Depth (this includes the surface atmosphere and is measured in ATA)

To find the desired component, merely cover the missing variable, dividing or multiplying as appropriate.

3.2.2 How Deep Can One Go?

If the available mix is known, and the PO_2 to which one is comfortable exposing one's body (no more than 1.4 ATA's for dives under a workload) is known, then the following formula can be used to establish maximum diving depth:

$$D\ (ATA) = PO_2/FG \qquad (3.7)$$

In other words, depth equals the partial pressure of oxygen divided by the fraction of the gas (your mix).[2]

Example: NOAA Nitrox I (32% oxygen) is the available mix. Because most dives involve swimming or unpredictable effort it is recommended to maintain 1.4 PO_2 or less.

How deep can one go?

$D = PO_2/ FG$

$D = 1.4/.32$ (32% must first be converted to decimal form)

$D = 4.38$ ATA's

Note: In this formula, the depth is expressed in ATA, which must be converted as follows:

fsw = (ATA - 1) x 33 (Subtract 1 for the atmosphere)

Therefore, from the example:

Imperial Example	Metric Example
fsw = (ATA - 1) x 33	msw = (ATA - 1) x 10
fsw = (4.38 - 1) x 33	msw = (4.38 - 1) x 10
Dfsw = (3.38) x 33	Dmsw = (3.38) x 10

= 111.54 fsw (33.8m). This should be rounded to 111 fsw (33m) for greater conservatism with respect to PO_2.

3.2.3 What Mix Should One Use?

Given one's maximum depth, and the PO_2 one is comfortable diving (typically no more than 1.4 ATA's), the best mix for a dive can be derived by using the following formula:

$$FG = PO_2 / D\ (\text{in ATA}) \qquad (3.8)$$

In other words, the fraction of gas equals the partial pressure of oxygen, divided by depth.

Example: Given both a wide range of available Nitrox mixes and the requisite training, what is the best possible mix to make a dive to 100fsw (30msw) (assuming no more than 1.4 ATAs PO_2)?

Imperial Example	Metric Example
Data = (Dfsw / 33) + 1	Data = (Dmsw /10) + 1
100'/ 33'= 3.03 ATA	30m / 10 = 3 ATA
Data = 3.03 + 1	Data = 3 ATA + 1

2 We find this formula by covering the missing D in the T formula above.

Data = 4.03 ATA

Data = 4 ATA

FG = PO_2/ D

FG = 1.4/4.03

FG = 0.347

In this example, the maximum oxygen content possible for this mix would be 33%. This is because rounding up would expose the diver to a pressure of oxygen greater than 1.4 PO_2, and it is always best to encourage conservatism with regards to oxygen PO_2. There is no need to push any limits, especially since minor changes in oxygen PO_2 offer minimal decompression advantage.

3.2.4 What is the PO_2?

Given both the maximum depth and the mix one is using, one can determine the partial pressure of oxygen by using the following formula:

PO_2= D x FG

In other words, the partial pressure of oxygen equals the depth multiplied by the fraction of the gas (mix).

Example: One wants to dive to 90fsw (27m) using NOAA Nitrox II (36% oxygen). What is the partial pressure of oxygen?

Adjusting the depth for ATA one gets:

Imperial Example	**Metric Example**
Data = (Dfsw / 33) + 1	Data = (Dmsw / 10) + 1
Data = (90 / 33) + 1	Data = (26.6 / 10) + 1
Data = 2.7 + 1	Data = 2.7 + 1
Data = 3.72 ATA	Data = 3.7 ATA

Using the established information from above:

PO_2= 3.72 x .36 (don't forget to convert mix to decimal)

PO_2= 1.34 ATA

In light of Central Nervous System (CNS) toxicity limitations, how long can one stay down on this mix? As will be explained in the next chapter, the commonly accepted answer is 120 minutes. Most divers will reach their personal air limits before reaching CNS restrictions. Of course, even with Nitrox, two hours at 98fsw requires substantial decompression.

3.3 There's Got To Be an Easier Way: MOD Planners

In school, the student is often made to do math by hand even though s/he owns a calculator. On the preceding pages are diving calculators, one imperial, one metric; they are MOD (Maximum Operating Depth) planners, and will serve to give divers the best mix and PO_2. Air, NNI 32%, and NNII 36% are shaded, whereas technical mixes are shown in white. Despite their ease of use, it is important to note that charts are best used as a check of one's own calculations, not as a replacement for them. If one does not

TABLE 3.4 MAXIMUM OPERATING DEPTHS: IMPERIAL

PO2 \ MIX	21	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	50	100
1.00	124	99	94	89	85	81	77	73	70	67	64	61	29	56	54	52	50	33	0
1.10	140	112	107	101	97	92	88	84	80	77	74	71	68	65	63	60	58	39	3
1.20	156	125	119	114	108	104	99	95	91	87	83	80	77	74	71	69	66	46	7
1.30	171	139	132	126	120	115	110	105	101	97	93	90	86	83	80	77	74	52	10
1.35	179	145	138	132	126	121	116	111	106	102	98	94	91	87	84	81	78	56	12
1.40	187	152	145	138	132	126	121	116	111	107	103	99	95	92	89	85	83	59	13
1.45	195	158	151	144	138	132	127	121	117	112	108	104	100	96	93	90	87	62	15
1.50	203	165	157	150	144	138	132	127	122	117	113	108	105	101	97	94	91	66	17
1.55	211	172	164	156	150	143	138	132	127	122	117	113	109	105	102	98	95	69	18
1.60	218	178	170	163	156	149	143	137	132	127	122	118	114	110	106	102	99	72	20

Due to rounding, some of these figures are one foot low, making them more conservative. Although charts are inherently less accurate, they typically maintain a perfectly reasonable margin of error. While charts do allow divers to forgo mathematical calculations, divers often forget to bring these charts to the dive site. It is important for divers to understand how to calculate their diving limits.

TABLE 3.5 MAXIMUM OPERATING DEPTHS: METRIC

	MIX																		
PO2	21	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	50	100
1.00	38	30	28	27	26	24	23	22	21	20	19	19	18	17	16	16	15	10	0
1.10	42	34	32	31	29	28	27	25	24	23	22	21	21	20	19	18	18	12	1
1.20	47	38	36	34	33	31	30	29	28	26	25	24	23	22	22	21	20	14	2
1.30	52	42	40	38	36	35	33	32	31	29	28	27	26	25	24	23	23	16	3
1.35	54	44	42	40	38	37	35	34	32	31	30	29	28	26	26	25	24	17	4
1.40	57	46	44	42	40	38	37	35	34	32	31	30	29	28	27	26	25	18	4
1.45	59	48	46	44	42	40	38	37	35	34	33	31	30	29	28	27	26	19	5
1.50	61	50	48	46	44	42	40	38	37	35	34	33	32	31	29	28	28	20	5
1.55	64	52	50	47	45	43	42	40	38	37	36	34	33	32	31	30	29	21	6
1.60	66	54	52	49	47	45	43	42	40	38	37	36	34	33	32	31	30	22	6

Due to rounding, some of these figures are one meter low, making them more conservative. Although charts are inherently less accurate, they typically maintain a perfectly reasonable margin of error. While charts do allow divers to forgo mathematical calculations, divers often forget to bring these charts to the dive site. It is important for divers to understand how to calculate their diving limits.

understand or cannot calculate these parameters on one's own, one should not be diving until one can do so.

3.3.2 How Does it Work?

To see how simple the MOD chart is, let us reexamine the previous examples.

Example: NOAA Nitrox I, 32% oxygen is the available mix, and the one is limiting oneself to a 1.4 PO_2. How deep can one go?

First, find the mix (32) to be used on the top line. Second, find the PO_2 (1.4) to be used on the left-hand side of the chart. Read vertically down from the mix and horizontally to the right on the PO_2. The intersection of the two (111fsw/34m) is the Maximum Operating Depth.

Example: Having technical Nitrox mixes available, and the training to use them, what is the best possible mix to make a dive to 100fsw (31m) without exposing one's body to more than 1.4 ATA's PO_2? Using the MOD chart, this problem is quickly solved. First, find the PO_2 (1.4) to be used. Second, read horizontally across to the right, finding a depth of 100 feet (31m), or the next deeper depth if the correct number is not available (103 feet). Then, third, read vertically up to find the recommended mix (34 percent). When forced to choose between columns it is always better to dive a mix that will result in a lower PO_2 at depth.

Example: One wants to dive to 90fsw (27m) using NOAA Nitrox II (36% oxygen). What is the partial pressure of oxygen?

Again, using the MOD chart, one can quickly find a solution. First, find the mix (36) at the top of the chart. Second, read vertically down to the depth (90feet/ 27m) or the next deeper depth (91feet/28m). Third, read horizontally to the left to find the PO_2 (1.35).

3.4 More About Nitrox

While Nitrox is relatively easy to dive, one may be wondering whether there are any further advantages to diving Nitrox. Once again, it is important for divers to understand that Nitrox and its benefits are based on sound theory and empirical research.

3.4.1 The Concept of Equivalent Air Depth (EAD)

As mentioned earlier, Nitrox works by adding oxygen to air, thereby decreasing the amount of nitrogen in a breathing gas. From this emerges a seemingly complex formula that gives a mathematical value to the benefit derived from using Nitrox. This formula converts real depth in the water to an equivalent depth based on the amount of nitrogen left in the gas. The formula is as follows:[3]

Imperial Example	**Metric Example**
EAD = [(N / .78) x (Dfsw + 33)] –33	EAD = [(N / .78) x (Dmsw + 10)] – 10

A closer look at this formula shows that it not as complex as it looks. What it reflects is the ratio of the nitrogen in the mix to that of nitrogen in air (N / .78), multiplied by actual depth plus one atmosphere (to account for the surface pressure), then taking the atmosphere back off at the end to convert back to depth in the water. Let's look at an example.

Example: A diver dives to 105fsw (32m) on NNII (36 percent). What is his/her Equivalent Air Depth?

Imperial Formula[4]	**Metric Example**
EAD = [(N / .78) x (Dfsw + 33)] –33	EAD = [(N / .78) x (mfsw + 10)] -10
EAD = [(.64/ .78) x (105 + 33)] – 33	EAD = [(.64/ .78) x (32m + 10)] - 10
EAD = [(.81) x (138)] – 33	EAD = [(.81) x (42)] - 10
EAD = [112] – 33	EAD = [34] - 10
EAD = 79 fsw	EAD = 24 msn

3.4.2 Calculated Advantage

This formula indicates that, as far as nitrogen is concerned, a dive to 105fsw (32m) on NNII will be similar to a dive to 79fsw (24m) on air. Though the diver will be as affected by narcosis as though he were at 105fsw (32m) on air, s/he will absorb nitrogen into her/his tissues as though s/he were at 79fsw on air (24m). From a decompression standpoint this advantage can be significant.[5]

A diver using NNII could use 80fsw (24m) as the max depth for purposes of decompression planning. Using conventional Navy tables that give an NDL of 40 minutes for 80 fsw (24m), (instead of only 20 minutes at 110fsw (32m)), the Nitrox diver is able to double his/her bottom time. Alternatively, one could be conservative and pretend the dive was at 90fsw (27m), 100fsw (30m), or 110fsw (32.81m), building in additional conservatism, as required.

3.4.3 The T Formula and EAD Chart

How about giving the T formula a try?

$\underline{\text{PG } (PO_2)}$

FG (%) x D (ATA)

For example, if one were diving a 36% Nitrox mixture, then 64% would be the remaining Nitrogen in one's gas supply. To calculate the partial pressure of N_2, multiply .64 by the depth (say 100fsw/30m) in ATA [64 x 4.03= 2.58 PN_2]. So, what would be the Equivalent Nitrogen Depth for a PN_2 of 2.58? Remember that the normal N_2 percentage is .78. Therefore, calculate 2.58/ .78 = 3.26. Given a total pressure of 3.26 – 1 x 33' for the surface (for the conversion to fsw or x 10m for metric), an Equivalent Air depth of 80fsw (23m) is reached.

The following EAD chart is provided to allow divers to cross-check their answers. To use this chart, first, find the mix on the top line. Then find the actual bottom depth in the column on the left. Read vertically

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3 N = decimal amount of Nitrogen in mix
4 N = Nitrogen in mix = 1.0-.36 = .64
5 With respect to the narcotic properties of oxygen, refer to the section on oxygen narcosis for more information.

down from the mix and horizontally across to the right from the depth. Where these two values intersect, one finds the EAD.

For example: A diver dives to 105ft (32m) on NNII (36 percent). What is his/her Equivalent Air Depth?

Find mix (36%) at the top, find actual depth (105ft/32m) or the next greater depth (106ft) in the left column. Read down from 36% and across to the right from 106ft to where these values intersect at 80ft or 24m.

TABLE 3.6 EQUIVALENT AIR DEPTH (EAD)

M I X

		25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	50	46	45	44	43	42	41	39	38	37	36	35	34	33	32	31	30
	55	51	49	48	47	46	45	44	43	42	41	39	38	37	36	35	34
	60	55	54	53	52	51	49	48	47	46	45	44	42	41	40	39	38
	65	60	59	58	56	55	54	53	51	50	49	48	46	45	44	43	41
	70	65	63	62	61	60	58	57	56	54	53	52	50	49	48	47	45
	75	70	68	67	65	64	63	61	60	59	57	56	54	53	52	50	49
	80	74	73	71	70	69	67	66	64	63	61	60	59	57	56	54	53
	82	76	75	73	72	70	69	67	66	65	63	62	60	59	57	56	54
	84	78	77	75	74	72	71	69	68	66	65	63	62	60	59	57	56
	86	80	78	77	75	74	72	71	69	68	66	65	63	62	60	59	57
	88	82	80	79	77	76	74	73	71	70	68	67	65	63	62	60	59
	90	84	82	81	79	78	76	74	73	71	70	68	67	65	64	62	60
	92	86	84	83	81	79	78	76	75	73	71	70	68	67	65	64	62
	94	88	86	84	83	81	80	78	76	75	73	71	70	68	67	65	63
	96	89	88	86	85	83	81	80	78	76	75	73	72	70	68	67	65
	98	91	90	88	86	85	83	81	80	78	76	75	73	71	70	68	66
	100	93	92	90	88	87	85	83	81	80	78	76	75	73	71	70	68
	102	95	93	92	90	88	87	85	83	81	80	78	76	75	73	71	70
D	104	97	95	94	92	90	88	87	85	83	81	80	78	76	75	73	71
	106	99	97	95	94	92	90	88	87	85	83	81	80	78	76	74	73
E	108	101	99	97	96	94	92	90	88	87	85	83	81	79	78	76	74
	110	103	101	99	97	96	94	92	90	88	86	85	83	81	79	77	76
P	112	105	103	101	99	97	95	94	92	90	88	86	84	83	81	79	77
	114	107	105	103	101	99	97	95	94	92	90	88	86	84	82	81	79
T	116	108	107	105	103	101	99	97	95	93	91	90	88	86	84	82	80
	118	110	108	107	105	103	101	99	97	95	93	91	89	87	86	84	82
H	120	112	110	108	106	105	103	101	99	97	95	93	91	89	87	85	83
	122	114	112	110	108	106	104	102	100	98	96	95	93	91	89	87	85
	124	116	114	112	110	108	106	104	102	100	98	96	94	92	90	88	86
	126	118	116	114	112	110	108	106	104	102	100	98	96	94	92	90	88
	128	120	118	116	114	112	110	108	106	104	102	99	97	95	93	91	89
	130	122	120	118	116	113	111	109	107	105	103	101	99	97	95	93	91
	132	124	122	119	117	115	113	111	109	107	105	103	101	99	96	94	92
	134	126	123	121	119	117	115	113	111	109	107	104	102	100	98	96	94
	136	127	125	123	121	119	117	115	112	110	108	106	104	102	100	97	95
	138	129	127	125	123	121	119	116	114	112	110	108	106	103	101	99	97
	140	131	129	127	125	122	120	118	116	114	112	109	107	105	103	101	98
	142	133	131	129	126	124	122	120	118	115	113	111	109	107	104	102	100
	145	136	134	131	129	127	125	122	120	118	116	113	111	109	107	104	102
	150	141	138	136	134	131	129	127	125	122	120	118	115	113	111	108	106
	155	145	143	141	138	136	134	131	129	126	124	122	119	117	115	112	110
	160	150	148	145	143	140	138	136	133	131	128	126	123	121	118	116	114
	165	155	152	150	147	145	142	140	137	135	132	130	127	125	122	120	117
	170	160	157	155	152	149	147	144	142	139	137	134	131	129	126	124	121
	175	164	162	159	157	154	151	149	146	143	141	138	136	133	130	128	125
	180	169	167	164	161	158	156	153	150	148	145	142	140	137	134	131	129

Chapter 4

The Logistics of Diving Mixtures Other Than Air

4.0 Operational Aspects

Diving with air is a well-established practice; this makes some divers feel that using other gas mixtures for diving is too complicated to be worth the trouble. Actually, the logistics of diving Nitrox are only slightly more complex than those of air diving. Most of these additional complications reflect the relative novelty of Nitrox diving, and the slow response of certain sectors of the diving community to embrace its use.

In order to safely dive Nitrox, the following issues must be addressed:

Nitrox can be prepared in many different ways.

Special precautions must be taken when dealing with elevated concentrations of oxygen.

Nitrox is not as widely available as air.

Great care must be taken to identify and label oxygen content and Maximum Operating Depth

Tanks used for Nitrox must be clearly labeled to avoid confusion and accidental misuse.

Divers must be familiar with the use of Nitrox in calculating decompression tables.

4.1 Nitrox Fill Techniques

Most divers will have their Nitrox tanks filled by a trained, qualified gas blender. The risk, aggravation, and expense associated with untrained divers filling their own tanks often overrides its perceived benefit. While the mixing process is not inordinately complicated, the average diver is usually best served by seeking a professional filling station wherever one is available. Qualified individuals can minimize the risk of Nitrox preparation by using proper instruments and procedures.

The perceived benefits of casual filling often overlook the true costs of this activity. Unperceived costs include wasted gas (supply bottles left with insufficient useful pressure), bottle rental, filling assembly equipment, wasted gas from incorrectly prepared mixtures, and the risk/trouble associated with having oxygen in one's home. While many technical divers successfully mix their own breathing mixtures, the average diver prefers the ease and support of local facilities.

4.1.1 Air Quality Concerns when Filling Nitrox

Regardless of any other constituent gasses, divers should always be concerned about the cleanliness of the air they breathe. Quality standards are well-established, and fill stations should maintain a solid system of maintenance and air checks for their compressor and for the air they pump. Divers should always patronize locations that maintain quality breathing gasses.

While cleanliness is a relative term, poor purity standards might increase the risk of combustion when blending Nitrox (due to increased oxygen content). However, divers should remember that poor purity standards produce other risks, such as carbon monoxide poisoning, and that breathing supplies should always be of high purity. Though most individuals know that a higher level of cleanliness is desirable, their general knowledge about air purity and the blending process is lacking. In light of this, it is important to raise the following question, "At what point does oxygen compatibility become an issue?"

Although not scientifically established, the consensus in the SCUBA industry is that special cleaning procedures are not necessary for mixtures with less than 40% oxygen. Nonetheless, anything that comes in contact with elevated oxygen levels may need greater levels of purity.[1] Two areas of concern here are the diver's equipment and a compressor's breathing supply. These concerns led to equipment that is specially prepared for use with elevated oxygen content (may be said to be *oxygen compatible*) and to specially purified air (may be called *oxygen-compatible air*).

There is notable debate about the degree of risk associated with elevated oxygen content. However, it is widely accepted that when coming into contact with elevated oxygen, equipment and air contaminated by hydrocarbons are more likely to be problematic. While divers often disagree on the level of cleaning necessary to prepare for elevated oxygen content, most individuals agree that properly cleaned equipment and high quality air should be an established standard, regardless of the breathing mix utilized.

The reasoning behind oxygen-compatible air is based on two possible hazards associated with mixing oxygen and air:

> *1. Oxygen fire*: An oxygen fire can occur during filling if sufficient levels of hydrocarbons encourage a lowered ignition point. High oxygen content and elevated fill temperatures facilitate this lowered ignition point.
>
> *2. Production of unwanted gasses during the filling process*: Gasses like CO and CO_2 can be produced when hydrocarbon combustion occurs inside the SCUBA cylinder. This can go unnoticed by the filler, but can have serious consequences for the diver; small quantities of these gasses can have large effects at elevated pressures.

These potential hazards pose a significant danger to both the air station attendant and the diver, but appear less likely when using proper procedures and air with elevated purity.

Air that does not officially fall within the parameters established for what is "oxygen compatible" can still be reasonably pure. Nonetheless, having an established set of parameters allows individuals to verify that the air they breathe has acceptably low levels of hydrocarbon contamination.

There are two principle solutions to producing "hydrocarbon reduced" air. The first is to use an "oil-free" compressor, which prevents hydrocarbons from coming into contact with the air one pumps. In the diving industry, these are commonly known as Rix compressors. Although this type of compressor seems highly suitable for blending, it has not gained popularity. This lack of popularity is due to a high initial purchase cost and a more rigorous schedule of maintenance, both of which encourage the belief that these systems are unnecessary. The second is to use a conventional oil-lubricated compressor in conjunction with "double filtration." This system incorporates the regular set of air filters along with another set of "hyper filters" to ensure a reduced quantity of hydrocarbons. Both methods produce a quality of air above the set standard for

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1 Later sections on oxygen cleaning discuss this issue in more detail.

regular breathing air and are designed to avoid the risk of ignition from elevated oxygen content.

The Compressed Gas Association (CGA) lists several grades of breathing air. Grade E is the standard for normal "breathing air." The oxygen-compatible standard was initiated by the SCUBA industry in response to concerns over potential oxygen fires. When we examine these figures, it is important to note that most concerns focus on oil particles; gaseous hydrocarbons play a secondary role.

Double filtration is quite common in the SCUBA industry. The primary filter group generally produces common "breathing air" and consists of two stages: mechanical separation and chemical absorption.

TABLE 4.1 AIR COMPOSITIONS[2]

CGA GRADE E (normal breathing air)	Content	O2 Compatible Air	Content
Oxygen	19-23%	Oxygen	20-22%
Carbon Monoxide	10ppm	Carbon Monoxide	2ppm
Carbon Dioxide	500ppm	Carbon Dioxide	500ppm
Gaseous Hydrocarbons	N/S	Gaseous Hydrocarbons	25ppm
Oil mist particles	5mg/m^3	Oil mist, particles	0.1 mg/m^3

Mechanical separation is accomplished by cooling the gas as it leaves the compressor. This process condenses much of the moisture in the air stream. A separator coalesces the oil and water vapor into droplets, which are then removed through the bottom of the canister at set time intervals (either manually or automatically). Properly running compressors will "hiss" every 10-15 minutes as they eject the water mixture.

Following mechanical separation, chemical absorption removes the remaining residue. Chemical absorption is the most effective method for removing moisture, oil vapor, and most gaseous contaminants. There are different types of filter media that can be used for this stage: silica gel, molecular sieve, activated carbon, and hopcalite. Silica gel or molecular sieve methods are primarily used to dry the air, activated carbon is used to remove hydrocarbons, and hopcalite is used as a catalyst to convert CO into CO_2.

Once CGA Grade E breathing air is produced by the above method, further filtration is required to produce

2 When examining these figures it is important to note that the primary focus here is on oil particles; gaseous hydrocarbons play a secondary role.

oxygen-compatible air. This is usually accomplished by adding a secondary filtration stack. Some systems use a large filter with more desiccant (molecular sieve) followed by activated carbon. Other systems avoid the addition of a large desiccant stack, but use the activated carbon filtration, arguing that the air does not need to be drier for filling Nitrox. However, a molecular sieve is able to remove oil vapor and dust particles.

Several filtration methods can provide sufficient levels of filtration. What is key is that one carefully chooses a reputable facility that is dedicated to providing clean and reliable gas fills. These facilities typically post recent (every three months) air analysis reports, and should always be happy to share the reports with those concerned.

4.2 Special Preparations for Elevated Oxygen Concentrations

Contrary to popular belief, oxygen is not flammable. Nonetheless, oxygen can act as a catalyst for greatly accelerating the intensity of a fire. Because of this, it is always prudent to exercise greater care around elevated oxygen levels. Somewhat arbitrarily, NOAA regulations and common experience have established that mixtures with oxygen content above 40% pose a greater risk to those concerned, and recommend that, in such cases, equipment be *oxygen clean*.

While some individuals prefer oxygen cleaning whenever the oxygen content exceeds 21% (air), common practice suggests that divers can treat mixtures below 40% in a similar way as a responsible diver would treat air. This would include getting fills from a reputable facility that both tests air quality and, on a monthly basis, posts its analysis results. In the end, the debate over oxygen cleaning is less a disagreement over whether equipment should be clean; rather, it is a debate over inconsistency and the erroneous application of existing guidelines. For example, equipment that is "oxygen clean" is no longer "oxygen clean" when filled with air that is not classified as oxygen-compatible. In practice, few divers follow this guideline; meaning that for them to conform to the existing guidelines, after each such fill their equipment would have to be "oxygen cleaned." Divers should seek facilities that fill tanks with oxygen-compatible air or air of similar quality.

4.3 Oxygen Cleaning

What people understand by "oxygen cleaning" varies greatly. In the diving world, the term oxygen cleaning is well-known, nonetheless, divers differ greatly with respect to what this means exactly or how to accomplish it. At one extreme, it is individuals in special outfits cleaning in "clean rooms"; at the other it is individuals "cleaning" in filthy conditions surrounded by an array of contaminants. In any case, it is likely that a sensible approach toward oxygen cleaning will reap the greatest rewards, and that attention to it will provide acceptable results.

While the consensus in the SCUBA industry is that oxygen cleaning below 40% is not necessary, nonetheless, many divers find it more practical to establish uniform cleaning guidelines for all their equipment. Rather than dedicate a specific regulator to a specific function, most divers maintain equipment equally and use it interchangeably. Therefore, should an equipment failure cause one component to be moved into oxygen service, the diver need not be concerned about varying cleaning parameters.

While silicone grease and hydrocarbons are two common contaminants, lint, rust, and other particles can also provide additional sources of ignition or fuel. *Oxygen serviced* is a term that refers both to the cleanliness of the piece of equipment and to the components used in the piece of equipment. Technically speaking, a component is "oxygen serviced" if it has been oxygen "cleaned" and assembled with oxygen "compatible" components. A service technician is most qualified to perform this function.

Oxygen cleaning is done by thoroughly cleaning the component of dirt and/or debris that could act as either an ignition source or as fuel for an oxygen fire. This should include a careful inspection of the component with magnification and a bright light to visually ensure that all debris has been removed. The component must then be assembled with oxygen-compatible parts. For example, standard o-rings and lubricants should be replaced with oxygen-compatible elements such as Viton® or Nitrile® o-rings and Crystolube® or Krytox® lubricant.

When mixing by partial pressures, the tank and valve assembly must be oxygen clean because they will be exposed to pure oxygen regardless of the final fill percentage. For example, a 32% Nitrox mix prepared by partial pressure methods requires an oxygen clean valve and tank because it is the result of topping off pure oxygen with air. To do this requires that:

> The tank and valve must be thoroughly cleaned to remove all particles, oil and grease.
>
> The standard o-rings must be replaced with o-rings made of Viton® or Nitrile®.
>
> The tank should be dedicated to Nitrox service and not allowed to come in contact with air that is not oil free.[3]

Other fill methods discussed in the following chart may not require oxygen clean tanks, as they do not necessarily expose your tank to concentrations of oxygen greater than 40%.

Common practice might suggest that while a 32% partial pressure Nitrox fill requires the tank to be oxygen clean, but not the regulator, a 32% Nitrox mix filled from a bank system would not require any oxygen cleaning at all. On this question, regulations and recommendations vary among agencies, governments, and individuals.

In summary, the consensus in the dive industry is that oxygen cleaning is not required for equipment that does not come into contact with oxygen levels higher than 40%. Nonetheless, to avoid the complexities of gear dedication, a much more reasonable course of action would be to maintain all one's equipment in same fashion and use it interchangeably. This would commit one to maintain all one's equipment "clean" and fill only where there is pure breathing air.[4] Maintaining clean equipment and visiting quality filling stations should be common practice for all divers, regardless of the breathing gas utilized.

4.4.0 Preparing Nitrox

There are several ways to safely prepare Nitrox. The following table is a brief overview of the most common Nitrox fill techniques. Each method has advantages and disadvantages.

4.4.1 Nitrox Availability Limited

While Nitrox use has become more common, there is still a shortage of qualified Nitrox fill stations. Nonetheless, there are several very popular methods for mixing Nitrox, any of which is acceptable. If one's tanks are oxygen clean, those tanks will be compatible with any of the most common Nitrox mixing procedures.

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3 Most dive shops do not provide completely oil-free air. If an oxygen clean tank is filled at a typical air fill station, it could become contaminated.
4 The idea of specific equipment to be used with different percentages in certain applications and filled at special places is unlikely to work in practice.

TABLE 4.2 NITROX MIXING TECHNIQUES

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Partial Pressure mixing: In this technique, a predetermined amount of pure oxygen is put into an oxygen clean tank and topped of with oxygen compatible air.	-Least costly setup -Medium operating cost -Little modification needed to existing air fill station	-Exposes the customers tank to pure oxygen -High pressure pure oxygen is being handled constantly
Continuous Mixer: In this technique, oxygen and air are mixed at the inlet of an oxygen compatible, oil free compressor, then compressed into tanks or storage cylinders.	-As quick as typical fills -May use low pressure oxygen for mixing	-Oil free compressors are much more expensive than oil lubricated compressors -Usually requires banks to be efficient
Membrane produced Nitrox: Operators pass air through a membrane filter that removes a variable content of nitrogen, producing greater percentages of oxygen-enriched air.	-Allows technicians to produce their own oxygen -Lack of high oxygen content reduces risk -No oxygen need be purchased -Does not require special compressors	-Purchase of membrane system can be cost prohibitive -Limited efficiency without low pressure source and high pressure pump to compress storage -Percentages greater than 36% become increasingly inefficient
Pre-blended storage: Nitrox is prepared ahead of time in large storage cylinders using one of the methods described above. The storage cylinders typically contain 40% or less oxygen, allowing attendants to fill from this supply or dilute it with air to lower the oxygen content.	-Never exposes customers tank to gas over 40% oxygen -Fastest for customer -Little modification needed to existing air fill station -No oxygen is handled around bystanders	-High operational cost due to boost pump drive air and filters -Requires additional oxygen clean storage cylinders -Preparation can be time consuming
Purchased pre blend: In this technique, the fill station operator buys Nitrox from a commercial gas supply house and dispenses as above.	-Same advantages as pre-blended storage -Lowest risk to fill station owner	-*Very* expensive

4.5 All Fills Must Be Analyzed

The end user must analyze his/her Nitrox fill, and should **never** trust other individuals (including shop personnel and dive buddies) to check the accuracy of their mixes. Divers should **never** pre-label a tank with the desired oxygen content, and to ensure maximum safety, should copy the oxygen content directly from the analyzer to the tank. Each tank must be labeled with the mixture and maximum operational depth. Individuals should carefully review the following section on tank labeling and gas switching procedures. Several talented divers have died because of sloppy filling, marking, or analysis practices.

4.6 Analyzing a Cylinder

Divers should always analyze their own cylinders to ensure the accuracy of their intended mixture. Using the wrong mixture because of either error or carelessness is the most significant risk to breathing elevated oxygen mixtures. Even minimal attention to detail can make this risk negligible.

When analyzing a mixture, divers should:

> Ensure that the tank is filled to the proper pressure. In the case of doubles, the isolator must be open.
>
> The analyzer should be calibrated. Calibration is usually done with air and set to 20.9.
>
> Gas should be run through the analyzer, usually with a flow meter at 3/8 to 1/2 liter/min. Temperature of gas for calibration should be the same as the gas analyzed. The probe needs to be at equilibrium temperature.
>
> Technically, mixes should be analyzed in the same manner as the gauge was calibrated. For example, analysis under flow (flow meter or tank valve outlet) should be coupled with calibration under flow conditions. However, common practice has found the difference in measured oxygen content to be negligible. Analyzing mixes with a flow meter from the tank does simplify the process and seems to encourage accuracy as a constant flow is easier to maintain.
>
> When the reading stabilizes, divers should copy the reading from the gauge to the tank. For example, 32.2% on the gauge should be copied exactly as it appears on the cylinder. This process is designed to ensure that the tank label represents the actual analysis rather than a pre-written target mix.
>
> The fill station's logbook should be signed, showing that the mix has been verified.

4.7 Tank Labeling

Dozens of divers have unwittingly breathed the wrong mixture for a particular depth and died because of it. Most often this involves divers breathing a richer-than-expected mixture (containing more oxygen) at depth and suffering from oxygen toxicity. At other times it involves either breathing a hypoxic (low oxygen) mix or the wrong decompression mix, with varying results. For some time following a tragic fatality of this kind, it is common that there is spirited debate over who or what is to blame for such errors.

Long ago, leading exploration divers recognized that, when using multiple mixtures, breathing the wrong mix at depth was the most significant risk to diving. Faced with the task of keeping a wide range of divers safe in highly variable settings, project leaders were forced to develop very simple and effective procedures. Directing international projects for Global Underwater Explorers, Jarrod Jablonski worked with Woodville Karst Plain Project Director George Irvine, to establish a set of fool-proof procedures for deep mixed gas diving operations. From deep ocean diving, to extended deep cave explorations, these groups have managed to establish a significant level of safety to historically dangerous activities.

Members of these organizations were keenly aware that breathing the wrong mixture at depth had taken the lives of several very experienced technical divers, and, therefore, presented a significant risk to team safety. Reviewing these fatalities indicated that most divers had not clearly marked their cylinders and/or did not follow an effective procedure for switching gas sources. For example, tank marking systems that relied on regulator markings, required divers to evaluate color differences, make underwater mental calculations, or identify bottles by touch, were dependant on a series of unpredictable variables. Regulators fail and need on-site replacement or regulators can be inadvertently placed on the wrong bottle; in both cases the result is a confusion of the diver's pre-determined identification system.

What Jablonski and Irvine saw was that the clear danger posed by these variable markings is that divers become accustomed to these markings and rarely refer back to the actual contents of their cylinders. Further, they saw that what was required here was a reliable marking system that was highly flexible, and thoroughly dependable, despite small changes in what equipment was used. This led them to embrace the uniform practice of marking cylinders with the Maximum Operating Depth (MOD) in a clear and easily identifiable manner, and utilizing only this information to identify bottles. This practice prevented divers from becoming accustomed to unreliable identification procedures.

4.7.1 Cylinder Marking: The Fine Points

Cylinders should be stripped of all unnecessary stickers (place VIP on bottom), Nitrox banners or other non-essential markings. Numerous markings create dangerous confusion.

Each cylinder should be marked horizontally on two sides with large three-inch high numbers identifying its MOD (Maximum Operating Depth).

Oxygen cylinders should be marked "20" with the word OXYGEN written horizontally along the tank, preventing divers from mistaking "20" with "70" or "120."

The diver's name should also be marked on the cylinders to simplify identification.

No gas percentages should be placed on the cylinder for identification purposes, as these require divers to make underwater calculations. Any content information is the result of analysis and should be placed near the neck of the bottle. For example, when analyzed, a 15.2% oxygen and 60% helium mixture would read 15.2/60; when analyzed, a 35% Nitrox mixture would read 35%.

The date analyzed and tester's initials should be included with the percentage marking.

4.8 Gas Switching Procedures

Any truly reliable tank identification system must work in concert with a dependable gas switching procedure. Divers that are not attentive and do not exercise caution while using different gas mixtures will inevitably use the wrong mixture at depth, possibly resulting in a fatality. The following gas switching procedures should always be followed:

Divers should operate as a team, verifying proper mixture and depth.

Arrive at the desired switching depth, retrieve and attach the cylinder if required (i.e. in a cave dive where bottles are left behind).

Locate the properly marked cylinder by checking the MOD marking and deploy its second stage (regulator is stored in an retaining band on the cylinder). Open the valve.

Remove the regulator being breathed but do not store it until a proper breathing supply has been established.

Place the proper regulator in the mouth.

If beginning decompression, start decompression time.

A sensible marking and deployment system is capable of ensuring that divers do not breathe the wrong mixture; nonetheless, this system must be supported by rational gas selection and sound mixing criteria. As outlined in earlier chapters, mixtures should never exceed 1.4 PO_2 unless divers are in a state of rest (i.e. during decompression). Furthermore, narcotic depths should be limited to 100 feet (30m) for diving and no greater than 130 feet (39m) for decompression. Whenever applicable, divers should adjust these limits in the direction of conservatism. Careless or overly aggressive oxygen limits and high narcosis levels expose divers to unnecessary risk.

Relying on personal experience and Doppler study, divers with extensive decompression experience have settled upon a set of standardized mixtures to be used during decompression; these are: 100 percent oxygen from 20 feet (6m), 50 percent oxygen from 70 feet (21m), 35 percent oxygen from 120 feet (36m), and 21 percent oxygen from 190 feet (57m). When not in use, all cylinder valves should be turned off with the hose pressurized and the regulator stored in the retaining band. If one cannot see the cylinder, and cannot properly identify the gas, DON'T BREATHE IT! The risk associated with breathing the wrong mixture is far greater than the minimal danger posed by less efficient decompression.

Chapter 5

Alternative Breathing Gasses

5.0 Background

For more than 100 years divers have been using mixtures other than air. In the last ten years, oxygen-enriched diving has started to become popular in the recreational diving community, while helium-enriched diving has finally begun to gain wider acceptance in the technical diving community. This is because air is not an optimal breathing mix. Air diving is plagued with an array of problems, ranging from narcosis to increased decompression and inefficient gas elimination. For these reasons, enriched oxygen mixtures, often in conjunction with helium, are the logical choice in the 30-100ft (10-30m) range, and helium-based mixtures are the optimal choice when deeper than 100ft (30m).

5.1 Definitions and Application of Mixed Gasses

Helium is an inert gas that for centuries has been used by commercial and military deep-sea divers to allow them to work at depths where air would be debilitating. In the last ten years helium has become increasingly popular among technical deep divers, and has a growing following among sport divers who wish to safely explore greater depths and/or enjoy increased comfort throughout the underwater spectrum. These divers are finding that helium allows them to enjoy safer, more pleasurable diving, as well as more efficient decompressions, reduced gas density and the elimination of dangerous narcosis.

Helium-based diving falls into three primary categories:

Triox- Triox is a helium-based gas with 21% or greater oxygen content.

Trimix- Trimix is any combination of oxygen, helium and nitrogen.

Heliox- Heliox is any combination of oxygen and helium.

Diving *Triox*, a helium-based gas with oxygen content of 21% or greater, is much like diving air, but without any narcotic impairment. It allows divers the benefit of helium-based gasses without the need for travel gasses or other decompression bottles, eliminating the risk that divers near the surface will experience *hypoxia* (not enough oxygen). Many divers appreciate the use of these mixes, i.e. 30/30, in areas shallower than 100ft. However, as divers approach 150ft (45m), they must reduce the oxygen content below 21% or risk oxygen toxicity. *Trimix* mixtures, in contrast, commonly have a reduced oxygen component so that they can be dived deeper without the risk of oxygen toxicity. Oxygen contents here usually range from 10% to 18%. However, oxygen contents below approximately 16% cannot be used near the surface without the risk of unconsciousness due to hypoxia. *Heliox* mixtures allow divers to eliminate all nitrogen and its associated narcosis. Historically, Heliox has been used very deep where even small amounts of nitrogen can be narcotic. Due to their high helium content, Heliox mixtures are less common outside commercial applications. Nonetheless, today, a growing number of dedicated technical divers are appreciating the benefits of increased levels of helium in their breathing mixtures.

Lastly, since deep helium-based mixtures normally contain very low oxygen content (less than 16%) those mixtures usually require the use of additional gasses for descent and decompression. This is because the low oxygen content does not allow the *bottom mix* (the mix that will be used at one's maximum depth) to be breathable near the surface. For this reason divers will use a "travel mix" to get to depth, one that contains the appropriate oxygen content. This is generally one of the diver's decompression mixes (usually the deepest available mix that contains sufficient oxygen content).

5.2 Principal Reasoning for Helium-based Diving Gasses

Decrease FN_2 while keeping a working PPO_2 near 1.4 at depths near 100ft (30m) to 150ft (46m).

Increase decompression efficiency by introducing helium and oxygen to displace nitrogen.

Reduce/eliminate narcosis.

Reduce density of the breathing mix; this results in both decreased work of breathing and reduced carbon dioxide retention. (Reduced work of breathing along with decreased CO_2 likely increases resistance to O_2 toxicity).

Research and practical experience indicate that helium's reduced molecular size improves decompression efficiency and limits decompression stress.

5.2.1 Misconceptions Associated With Helium Diving

Most assume that helium is complex to dive, the availability is limited, and that mixing Trimix or Triox is difficult. Furthermore, divers believe that complex, multi-course training is necessary for Triox diving and that helium is only for very deep diving with mixtures cannot be used at or near the surface. Perhaps the most dangerous of these inaccurate pereptions relates to the misconception that divers can and should strive to "manage" narcosis with training and/or practice.

5.2.2 The Reality of Mix Diving

Helium is not complex to dive.

Trimix blending is only slightly more complex than Nitrox blending.

Training to dive helium, in the moderate 100ft (30m) range, is very similar to training for Nitrox diving.

Many helium-based mixtures can be used at or near the surface.

Helium is not only for very deep diving, but has useful applications in the moderate depth ranges as well.

Complications of helium use are true of all proper deep diving; those complications are not exclusive to breathing helium.

Helium mixtures can greatly reduce narcotic impairment, and are far safer than diving air.

Immersion in a helium mixture rapidly conducts heat away from the body, making it essential to insulate dry suits with other gasses, such as argon.

The perceived complexity of helium actually reflects the difficulty of diving to greater depths, where multiple bottles of different mixtures are required.

Deeper diving, requiring multiple mixtures, demands a great deal of experience and skill well beyond the relative simplicity of helium as a diving gas.

The belief that one can “manage” narcosis is indefensible.

5.3 Historical Overview of Trimix Diving

1919: Patent issued for oxygen-helium breathing mixtures (Cooke)

1925: US Bureau Of Mines experiments with helium decompressions (Hidebrand, Sayers, Yant)

1937: First successful Heliox dive (End, Nohl)

1939: USN Heliox Tables published (Behnke)

Successful rescue and salvage of *USS Squalus* (240ft/74m)

1962: First commercial Heliox dive to 420ft/129m (Wilson)

First saturation dive to 200ft/61m (Link)

Hans Keller successfully demonstrates gas-sequencing techniques on a 1,000ft/307m bounce dive

1970: First recorded incident of High Pressure Nervous Syndrome (HPNS)

1988: Sheck Exley conducts his record open-circuit dive to 780ft/239m at Naciememto Del Rio Monte using Trimix and several Nitrox mixtures for decompression

1989: Parker Turner, Bill Gavin and Bill Main successfully complete the Sullivan Connection (240ft/74m) using Trimix/Nitrox mixes

1991: Billy Deans, founder of *Key West Diver*, offers the first open-circuit helium training

1992: First organized open water mix expedition on the *Andrea Doria* (250ft/77m) led by US East Coast wrecker Bernie Chowdhury

US East Coast wrecker Ken Clayton conducts a series of dives on the *Frankfurt* using *neox* (an oxygen-neon mix)

1986-present: The Woodville Karst Plain Project rapidly expands the use of helium diving, particularly in deep cave exploration. While specializing in deep cave diving, the WKPP has established nearly every significant cave diving record. The WKPP is responsible for nearly all exploration in the Woodville Karst Plain, including nearly all substantive exploration in the world’s largest cave, Wakulla Springs; dives beyond 18,000 feet (5,000m) of penetration at 300ft (90m) become commonplace. The WKPP’s efforts are augmented by the international research, education, and exploration activities of Global Underwater Explorers (GUE), formed by some of the WKPP’s founding members.

5.4 Nitrogen (N_2)

Air, and its pirnciple component, nitrogen, have been the mainstay of divers since the early years of diving. Inertia and simplicity tend to sustain its popularity, but when considering increased depth, most technical divers today have come to see mixes like air as inefficient and dangerous. This is largely because nitrogen creates substantial narcotic impairment with increased depth and as a consequence, most active explorers have abandoned it. Furthermore, especially at depth, nitrogen's density makes proper ventilation extremely difficult, making CO_2 retention and its associated problems issues that must be considered. For example, at 300ft (90m), air has a breathing resistance similar to what would be expected with Heliox at greater than 2,000ft (700m). These limitations, coupled with a poor lipid out-gassing rate, make air a poor choice for dives beyond about 100ft (30m). Above 100ft, most divers prefer to capitalize on the advantages of enriched-oxygen mixes, often by also adding helium to further reduce the presence of nitrogen.

5.4.1 Nitrogen Properties

Colorless, odorless, tasteless

Atomic number = 7

Atomic weight = 14.0067

Exists in a diatomic state (N_2)

Molecular weight of N_2 as it exists = 28.0134

Density r = 1.2504 g/l

Boiling point is – 194.6° C

Narcotic Potency = 1 (5 is least narcotic and 0 is the most)

Solubility in Lipid = 0.067

Thermal Conductivity = 60.34 cal/(sec)(cm^2)(°C/cm) x 10^{-6} at 60° F

Partial Pressure in Air is .78 bars, or 78% of air

Not involved in metabolism \ Physiologically inert

Increased Partial Pressure induces symptoms of narcosis or anesthesia

- Effects are measurable at approximately 30 feet (9m)
- Amplified impairment with increasing depth

5.4.2 Nitrogen Absorption, Diffusion and Other Considerations

Absorbs into tissues and fluids and may form bubbles during ascent.

Greater density can reduce diffusion efficiency.

Nitrogen is seven times denser than helium; this impacts a diver's ability to ventilate and remove CO_2, and limits work capability at depth. Breathing air at the surface is similar to breathing a Heliox mixture at more than 200ft (60m).

5.5 Helium (He)

The general public best knows helium for its speech distorting quality. As thinner gas passes across the vocal cords, it produces a high-pitched squeak, reminiscent of the cartoon character Donald Duck. In fact, any change in gas density can produce a similar effect. With respect to diving, helium's speech distortion is only relevant if divers are using audio communication devices. Helium has gained great recognition because of its very low narcotic potency, low density, and efficient lipid elimination. Helium-based gasses are easy to breathe at depth, increase decompression efficiency, and eliminate narcosis.

5.5.1 Helium Properties

Colorless, odorless, tasteless, rare gas

Atomic number = 2

Atomic weight = 4.0026

Exists in a monatomic state (He)

Molecular weight of He as it exists = 4

Density r = 0.179 g/l

Boiling point is –269° C (only 4° C above absolute zero)

Narcotic Potency = 4.26 (5 is least narcotic and 0 is the most)

Solubility in Lipid = 0.015

Thermal Conductivity = 352.10 cal/(sec)(cm^2)(°C/cm) x 10^{-6} at 60° F

5.5.2 Advantages of Helium

Elimination of narcosis.

Lower density provides substantially less breathing resistance (roughly 1/7 that of air).

Rapid off-gassing, with reduced assimilation by slow tissues.

Increased decompression efficiency.

5.5.3 Disadvantages of Helium

High Pressure Neurological Syndrome (HPNS). This manifests itself with tremors, muscle twitching and coordination difficultiesand usually occurs past the 400ft(120m) range.

Rare cases of hyperbaric arthralgia, an arthritic-like stiffness, can occur during descent.

5.5.4 Tissue Solubility

Helium enters tissues rapidly, up to 2.65 times faster than nitrogen. Therefore, helium-based diving mixtures require decompression stops that begin deeper than for air, with short stops at depth to eliminate the greater proportion of accumulated gas. As with most mixtures, helium decompressions can be reduced by the use of Nitrox and oxygen at shallower depths. Historically, divers have been instructed to switch from helium as quickly as possible, but more recent evidence indicates that the fear of prolonged helium use is unwarranted.

5.5.5 Thermal Loss

Helium-based mixtures contribute significantly to heat loss when divers are immersed in it (e.g., with dry suit inflation). Helium transmits heat very efficiently, with a thermal conductivity six times that of air. For this reason, divers should never fill suits with helium-based mixtures, as the risk for hypothermia and mental impairment are significant. Argon is the preferred gas for suit inflation, with air still being far preferable to helium inflation. Individuals should not underestimate the thermal loss of helium mixes or the subtle, but dangerous, impairment of hypothermia.

By direct conduction, the lower molecular density of helium transmits heat more readily than do air molecules. Therefore, a helium mixture entering the diver's lungs will be colder than air, because it has lost heat during its journey from the cylinder. In contrast, air's greater density will conduct heat more readily. So by comparison, air is denser and may feel warmer when inhaled at any given depth. However, air's greater density can conduct more heat over a relative volume of gas, potentially contributing more significantly to core heat loss than helium mixtures. In general, thermal heat loss is similar for both mixtures. These two effects seem to counteract one another. Generally speaking, then, thermal heat loss is similar for both mixtures.

5.5.6 High Pressure Nervous Syndrome (HPNS)

High Pressure Nervous Syndrome appears to be the consequence of a high-pressure gas gradient across tissue compartments, apparently compounded by helium breathing. HPNS can appear at depths shallower than 200ft (60m) but is most commonly experienced deeper than 400ft (120m). HPNS is influenced most notably by descent speed and individual physiology. Rapid descents such as those found in conventional diving can exacerbate HPNS symptoms. This phenomenon is particularly noticeable in the especially rapid compressions found in commercial bounce dives deeper than 400ft (no longer allowed by most regulations).

The most effective mechanism for reducing HPNS is to increase the descent time. In very deep diving (such as beyond about 400ft) this requires reducing the descent speed to levels only practical in bell diving. The addition of small quantities of nitrogen also appears to reduce or at least mask the symptoms of HPNS.

HPNS symptoms[1] include:

Muscle tremors

Drowsiness

Nausea

Dizziness

1 Several of these symptoms are actually common to several forms of gas toxicity or physiological stressors, (e.g. dizziness, nausea, loss of concentration) and can be confused with inert gas narcosis or oxygen toxicity.

Loss of appetite

Vertigo

Difficulty in concentrating

Visual disturbances

5.5.7 Helium Gas Density

Helium's low molecular density has several practical advantages. Reduced gas density produces better regulator performance (particularly at depth) and reduces CO_2 accumulation. Carbon dioxide has been implicated in deep-water blackout, may encourage CNS toxicity, and is a physiological stressor that can exacerbate stress and panic. Reduced gas density also reduces the work of breathing and may limit the impact of pulmonary toxicity symptoms. Given that Heliox density is roughly 1/7 that of air, even moderate dives in the 150ft (45m) range can enjoy substantial reductions in breathing resistance.

Divers using dense gasses, such as air, establish a dangerous loop wherein increased gas density elevates breathing resistance and stress, and triggers an increase in CO_2 levels. In turn, elevated CO_2 levels act as a narcotic that further depresses the respiratory function beyond what it is already experiencing because of nitrogen. This depressed respiration increases CO_2 levels, narcosis, and stress, which beget more of the same until the diver is fortunate enough to end the dive or circumstances preclude any conscious choice.

5.5.8 Helium Diving

Dr. Buhlmann is a well-known figure in the world of decompression modeling; many current decompression algorithms are based on his research. Buhlmann is particularly relevant to a discussion of helium because his efforts helped usher in the use of helium diving. As one of the first to advocate the use of helium, Buhlmann made great strides in the safe calculation of helium profiles. Ironically, however, he is also one of the individuals who encouraged great conservatism with helium, and perhaps inadvertently, the use of deep air; he did so by claiming that divers should switch off helium-based mixes as soon as possible, often at quite significant depth. This misconception, along with others, led divers to consider helium a gas to be used only during deep (in excess of around 250ft) diving.

During the early years of "recreational" deep diving (late 1980's and early 1990's), helium use was often discouraged, and an irrational fear existed regarding its use. This fear stemmed largely from ignorance and a few early problems well known to early deep divers (i.e. Hans Keller's fateful dive and Hal Watts' DCS-laden Mystery Sink dive).

During this time, most cave and wreck divers shunned the use of helium. Divers were frequently discouraged from using helium. They were told that it led to a much greater risk of CNS damage, and that there was no safe way to decompress from helium dives (actually the reverse is true; helium promotes efficient decompression). This early resistance to helium by early leaders in deep diving was widely disseminated, and further delayed the use of helium for deep diving. It was widely believed that if helium must be used, then divers should switch from it as soon as possible.

The perceived need to switch from helium early and deep, coupled with the idea that it was somehow a sign of toughness to manage nitrogen narcosis, led many divers to assert that individuals should be comfortable with air to at least 200ft (60m). Indeed, this concept is still maintained by several well-known deep divers. They claim that it is best to switch to air deep, and that emergencies may require the use of deep air.

The WKPP, GUE, and other divers ushered in a new era in helium diving by realizing that these switches were unnecessary and dangerous, and that there was no *need* for air diving at all, emergency or not. Instead, safety and efficiency were found to actually improve when one used a combination of helium mixtures and nitrox during every phase of one's diving; helium-mixtures below 100ft (30m), Nitrox shallower. This new perspective on mixed-gas diving freed divers to look at the application of helium in a variety of areas. Jarrod Jablonski and George Irvine, for example, pioneered the use of helium mixtures in unconventional situations; e.g. shallower than 100ft (30m), and during decompressions on very long immersions. This turn of events led to increasingly common helium diving in the shallow and intermediate ranges and beyond.

Through their cutting edge work with helium, explorers like Jablonski and Irvine have come to argue that popular dissolved gas models (such as Haldane and Buhlmann) were inaccurate and produced inefficient decompressions. Their argument is that these models treat helium in a highly conservative manner and that it is likely that this conservatism is not an accurate reflection of "reality", further highlighting the problems with dissolved gas calculations. In light of this, they contend that new "bubble models" such as the Varying Permeability Model (VPM) will demonstrate more realistic parameters.

In light of both the WKPP's and GUE's work with helium, it now seems evident that helium has been treated too conservatively, and that it is either eliminated more rapidly and/or is tolerated at higher pressure than what was originally believed. Jablonski and Irvine have not only demonstrated the clear benefits of increased helium use on very long immersions, they have also shown that these benefits extend beyond bottom mixes into helium-enriched decompression mixtures. Together with the WKPP, GUE divers are commonly using helium mixes with greater comfort and efficiency from short recreational diving to long immersion exploration dives.

5.6 Oxygen (O_2)

Of all the respiratory gasses (natural or otherwise), oxygen is the only truly indispensable one. Constituent gasses in any breathing mixture are largely carriers for oxygen metabolism, and each has their own particular limitation. Interestingly enough, the oxygen so vital to sustaining life is not particularly forgiving with respect to an operational range of partial pressures. Oxygen below about .16 initiates hypoxia, and around .10, unconsciousness. At the upper end, oxygen is used at partial pressures approaching 3.0, but only in dry chambers during hyperbaric treatment.

Oxygen is perhaps most troublesome because of the variable susceptibility to oxygen found within and among individuals. Oxygen toxicity tests show that tolerance to a given PO_2 can vary from hours to minutes in one individual across several days and among various subjects in a group. Fortunately, oxygen partial pressures below about 1.4 are more reliably tolerated, and the commonly accepted oxygen limits have been found to be reasonable for a broad range of individuals. However, the combined risk of CNS toxicity and pulmonary damage should motivate individuals to exercise great care in the management of oxygen exposures.

Oxygen makes up 21% of our atmosphere and was not discovered as a separate gas until the late 18th century.

1774: Joseph Priestley discovers oxygen

1783: Oxygen used as a remedy for the first time

1878: Paul Bert discovers oxygen toxicity

1899: Lorraine Smith discovers oxygen pulmonary toxicity

1942: Donald's work on over 2,000 exposures forms the current basis for exposure limits

5.6.1 Oxygen Properties

Colorless, odorless, tasteless, rare gas

Atomic number = 8

Atomic weight = 15.9994

Exists in a diatomic state (O_2)

Molecular weight of O_2 as it exists = 31.9988

Density r = 1.429 g/l

Boiling point is –183° C

It is 20.9 percent of the atmosphere and has a PP of 0.209 bars

Narcotic Potency = likely similar to nitrogen

Solubility in Lipid = 0.11

Thermal Conductivity = 61.58 cal/(sec)(cm^2)(°C/cm) x 10^{-6} at 60° F

5.6.2 Special Oxygen Considerations

Oxygen is active during the metabolic processes with CO_2 byproduct.

Evidence suggests that elevated pressures of oxygen produce anesthetic results similar to narcosis.

100% oxygen is used for accelerated decompression/hyperbaric treatments.

Special needs for equipment and tanks include:

- Oxygen Clean
- Oxygen Compatibility

High partial pressures of oxygen have some side effects, including:

- Central nervous system toxicity (CNS)
- CNS toxicity may result in a seizure while immersed
- Partial pressures of over 1.6 can be extremely dangerous
- 1.4 is the **maximum** for the working phase of a dive
- Lung tissue inflammation from long exposures, i.e. pulmonary toxicity
- Exposure with a 24-hour time frame has a damaging effect on the lungs
- High levels of O_2 can cause "lung burnout"
- Prolonged exposure to oxygen lowers the vital capacity of the lungs

5.7 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is the gaseous end-product of the aerobic metabolism of oxygen. It is highly soluble in body tissues, and readily diffuses from cells to blood where circulation transports it to the lungs for elimination. Divers often ignore carbon dioxide, since it is a normal part of life. However, with excessive accumulation, CO_2 can have definite and detrimental effects.

Carbon dioxide is a narcotic gas that can depress awareness; it can even lead to loss of consciousness. In humans, acute elevation of arterial PCO_2 (above 70 to 75 mmHg) reduces awareness, while $PaCO_2$ (above 100 to 120 mmHg) produces unresponsiveness. The narcotic potency of a gas is tied to its lipid solubility and CO_2 is 25 times more lipid soluble than nitrogen.

Furthermore, elevated CO_2 levels induce physiological stress, which can severely distract divers and/or initiate panic. It is highly likely that CO_2 was a significant factor in numerous unexplained fatalities, as well as possibly precipitating other dangers such as narcosis, DCI, CNS toxicity, panic, and loss of consciousness. Most seasoned divers will attest that elevated levels of CO_2 were a factor in many of their "close calls;" therefore, it would be prudent that all divers be wary of its risks.

5.7.1 Carbon Dioxide Properties

Colorless, odorless, tasteless gas

By-product of oxygen metabolism

Molecular weight of CO_2 as it exists = 44.01

Density r = 1.977 g/l

Boiling point is – 78.5 ° C

0.033% of the atmosphere

Narcotic Potency = anesthetic potency of about 130 times that of nitrogen

Solubility in lipid = 1.34

Thermal conductivity = 37.61 cal/(sec)(cm^2)(°C/cm) x 10^{-6} at 60° F

Physiologically controls primary breathing center

Excessive carbon dioxide levels in the blood leads to toxicity

Inefficient ventilation of the lungs leads to CO_2 retention, causing elevated CO_2 in the blood and tissues (hypercapnia)

Increased breathing resistance (excessive gas density or poor equipment) leads to high levels of CO_2 retention

At 1 ATA (1 bar/at the surface) short exposures of 3% can be tolerated; however, for long exposures, it must be limited to 0.5% (5 mbar)

CO_2 retention is implicated as a contributing factor in the following:

CNS toxicity

Increased risk of DCS

Higher susceptibility to narcosis

More likely to lose consciousness

5.8 Other Breathing Gasses

The challenge in establishing a proper gas mixture lies in how to provide the necessary concentration of oxygen while limiting the negative impact of other constituent gasses. There is very little reliable information regarding the use of other inert gas mixtures (other than helium and nitrogen) in diving applications. Nonetheless, there is very little incentive for most divers to consider the use of more exotic gasses. Fledgling research indicates that several other breathing mixtures could be substituted for helium and nitrogen, but these gasses have their own set of limiting parameters and have not been extensively tested. The information below is presented primarily for academic purposes.

5.8.1 Hydrogen (H_2)

Hydrogen mixtures have been successfully used in excess of 1600ft (500m). The most successful mixture involves the addition of helium and oxygen to create Hydreliox. Given that hydrogen is particularly explosive when mixed with more than 4% oxygen, it has no real applications in open-circuit diving. Furthermore, when used exclusively with oxygen, and at great depth, hydrogen has narcotic effects similar to LSD. Following deep diving trials, this mixture has been implicated in long-term psychological changes in saturation divers.

5.8.1.1 Hydrogen Properties

Colorless, odorless, tasteless

Atomic number = 1

Atomic weight = 1.0079

Exists in a diatomic state (H_2)

Molecular weight of H_2 as it exists = 2

Density r = 0.090 g/l

Lightest element on earth

Boiling point is – 253 ° C

Narcotic Potency = 1.83

Solubility in Lipid = 0.036

Thermal Conductivity= 433.92 cal/(sec)(cm^2)(°C/cm) x 10^{-6} at 60° F

Reacts violently with oxygen at concentrations greater than 4% of total volume

5.8.1.2 Special Hydrogen Considerations

Successfully used in depths in excess of 500msw (1600ft)

The most successful mixture involves adding helium and oxygen to hydrogen to create Hydreliox

When used exclusively with oxygen, and at great depth, hydrogen has narcotic effects more similar to LSD

Implicated in long term psychological changes in saturation divers following deep diving trials

5.8.2 Neon (Ne)

Neon may have some advantages for short duration deep diving, but it is expensive. Neon is denser than both helium and nitrogen, and diffuses more slowly into tissues than both gasses. Therefore, neon is theoretically useful for short bounce dives. However, it also emerges from tissues more slowly, and where long exposures are involved, decompressions can be extensive. Neox diving has very little data to support it; therefore how to gauge safe diving profiles and details of recompression therapy are unknown.

5.8.2.1 Neon Properties

Colorless, odorless, tasteless

Atomic number = 10

Atomic weight = 20.179

Exists in a monatomic state (Ne)

Molecular weight of Ne as it exists = 20.179

Narcotic Potency = 3.58

Solubility in Lipid = 0.019

Thermal Conductivity = 112.82 cal/(sec)(cm^2)(°C/cm) x 10^{-6} at 60° F

5.8.2.2 Special Neon Considerations

More dense than both helium and nitrogen, and diffuses more slowly than both gasses.

Theoretically useful for short bounce dives.

Emerges from tissues more slowly, and where long exposures are involved, decompressions can be extensive.

Neox diving has exceedingly limited data by which to gauge safe diving profiles and little is known about the details of recompression therapy.

5.8.3 Argon (Ar)

Argon is almost twice as narcotic as nitrogen, but may have some application as a decompression gas. Theoretically, by reducing the amount of inert gas counter diffusion into the tissues at depths greater than nine meters, shallow decompression stops could benefit from argox mixtures. However, there is very limited information and testing available to verify this claim. Argon is most commonly used as a gas for dry suit inflation where its density reduces heat loss.

5.8.3.1 Argon Properties

Colorless, odorless, tasteless

Atomic number = 18

Atomic weight = 40

Exists in a monatomic state (Ar)

Molecular weight of AR as it exists = 39.948

Narcotic Potency = 1.83

Solubility in Lipid = 0.014

Thermal Conductivity = 41.33 cal/(sec)(cm^2)(°C/cm) x 10^{-6} at 60° F

5.8.3.2 Special Argon Considerations

TABLE 5.1 BUNSEN SOLUBILITY COEFFICIENTS FOR COMMON GASSES

Gas	Bunsen Solubility Coefficient in Olive Oil, 22 C; ATA $^{-1}$
Helium	0.015
Hydrogen	0.042
Nitrogen	0.052
Oxygen	0.110
Argon	0.150
Krypton	0.440
Carbon Dioxide	1.340
Nitrous Oxide	1.560
Xenon	1.900

Preferred dry suit inflation gas when diving helium mixes.

Heat transfer capacity of about 66 percent of that of compressed air.

Argon is an important thermal protection advantage to dry suit divers.

Increases thermal protection up to as much as 40 percent.

Carried in a small inflation bottle (6-14ft^3, 1-2L), with regulator and inflation hose, overpressure relief valve, and removable argon mounting system.

Assuming that the suit is not used for buoyancy, a typical 200-300fsw dive, with bottom times up to 30 minutes, requires about 2-3ft^3 of inflation gas.

Argon Use Procedures:

Flush the air from the suit.

On the surface, fill the suit three to four times, flushing the air before the dive.

Inflation bottle should be clearly marked "Argon" to avoid inadvertent breathing, which would result in unconsciousness and/or death.

5.9 Gas Narcosis

Narcosis is everyone's enemy, the effects of which range from a subtle decrease in judgment to total incapacitation. Narcosis can be caused by a wide variety of agents, from simple gasses like xenon and nitrogen, to complex hydrocarbons used to produce general anesthesia. Although the narcotic effect of gasses has been studied for over 100 years, a full understanding of how they produce narcosis (and anesthesia) is lacking. In the case of nitrogen, much of what is known about its narcotic effect comes from the study of anesthetic gasses. Around 1900, Meyer and Overton independently observed that the potencies of general anesthetic gasses were tied to their solubility in a simple organic solvent, olive oil. These observations have become known as the *Meyer-Overton rule*, which predicts that the anesthetic potency of a gas is inversely related to its lipid solubility. In other words, more lipid soluble gasses produce narcotic effects at lower concentrations than less soluble gasses. Table 1 lists Bunsen's solubility coefficients for common gasses.

Thus, based solely on lipid solubility, helium should be the least narcotic gas, and nitrous oxide and xenon the most narcotic gasses. This is because in animals (including humans), the anesthetic potency of gasses closely parallels the lipid solubility of those gasses. For this reason, highly lipid soluble gasses, such as nitrous oxide and xenon, can be used as anesthetics at normobaric pressure.

Some interesting observations follow from this discussion of lipid solubility. Oxygen is twice as lipid soluble as nitrogen, and thus, should be twice as narcotic. However, oxygen is not inert, but metabolized; this means that the increase in the tissue partial pressure of oxygen does not parallel the increase in inspired oxygen partial pressure. In other words, there is less proportional narcosis with oxygen because oxygen is metabolized; the tissue oxygen partial pressure does not increase as it does with a non-metabolized gas. In contrast, carbon dioxide is also very lipid soluble, and has been used to produce anesthesia in animals. Increased arterial partial pressure of carbon dioxide above 60 mmHg produces narcosis in humans, and arterial PCO_2 greater than 100 to 120 mmHg may result in loss of consciousness.

Because the Meyer-Overton rule is based on lipid solubility, one can infer that gasses exert their narcotic effects by dissolving in cell membranes, which are composed of lipids. Like all cells, the neurons in the central nervous system (CNS) have lipid membranes as well as embedded proteins that serve as ion channels or receptors for extra-cellular compounds. Consciousness is controlled by the central nervous system (CNS), and alterations of function of the CNS can lead to a reduction in consciousness. By dissolving in the lipids, and by interfering with normal cellular function, lipid soluble gasses are considered to alter neuronal function. There are a number of mechanisms by which altering the lipid membrane could interfere with neuronal function; this would be by either directly altering the properties of the lipid membrane or by indirectly affecting the properties of embedded proteins. When anesthetic gasses dissolve in lipid membranes, they disrupt the normal closely packed ordering of the lipid molecules, resulting in an increase in the fluidity of the membrane. This increase in the area of the membrane may impinge on embedded proteins and interfere with their function.

As good as the Meyer-Overton rule is, it fails to predict the anesthetic potency of a number of compounds, and is likely an incomplete description of *in vivo* events. For example, with hydrocarbons such as alcohols, increasing the chain length of the hydrocarbon increases the lipid solubility, and the anesthetic potency, but only up to a point. With most organic compound series, when the chain length reaches 10 to 14 carbon atoms, there is a sudden loss of anesthetic effect. Thus, although the compound is lipid soluble, it does not produce narcosis. The Meyer-Overton rule cannot explain this sudden loss of anesthetic effect. In addition, molecular *isomers* (the same atoms, but arranged differently) of clinically-utilized anesthetics have identical lipid solubility, but different anesthetic potencies. Again, based on the Meyer-Overton rule, those isomers should have identical anesthetic potency. Based on these observations, there seem to be more factors involved in anesthetic effect of gasses than lipid solubility. Currently, what all of these factors are, and how gasses produce narcosis and general anesthesia, is not fully understood.

Many divers believe that they can "adapt" to narcosis by repetitive exposure. Actually, objective testimony of divers breathing air at 54.6msw (180fsw) once a day for five days showed that there was no adaptation in reaction time or procedure errors. However, over the same five days, there was reduced perception of narcosis. In other words, although the divers **felt** less impaired, there was no objective evidence that they **were** less impaired.

Depression of the central nervous system by illicit drugs, alcohol, and antihistamines may also exacerbate narcosis. Carbon dioxide retention can also exacerbate narcosis, and study of the interaction of carbon dioxide with nitrogen narcosis suggests that the two are additive. Drugs are easy to avoid, but carbon dioxide retention may be a less obvious problem. Arterial partial pressure of carbon dioxide may be elevated by a number of factors, including exertion at depth, gas density, rebreathing expired CO_2 (i.e. a large dead space in breathing equipment), restrictive suits, and regulators with high breathing resistance. Thus, divers should always be aware of the potential for carbon dioxide retention, as not only can carbon dioxide exacerbate narcosis, but it also can also precipitate a hyperoxic seizure.

Chapter 6

Oxygen - The Most Mysterious Gas

6.0 Introduction

Air is one of the least efficient gasses available for diving, and is no longer used by many technical divers. Even among novice divers air is losing popularity, with a growing number of divers learning to use Nitrox in their open water training. This movement away from air to helium and oxygen-based mixtures is revolutionizing diving, and making unconventional dives safer and attainable.

However, like air diving, using Nitrox and other breathing mixes is not without risk. Thus, understanding the history of oxygen risk allows divers to fully appreciate how to safely use various breathing mixes. Breathing mixtures with elevated oxygen content have three primary risks:

The possibility of breathing the wrong mix (covered in detail in the section on gas switches in Chapter 4, The Logistics of Diving Mixtures Other Than Air).

Not understanding the limitations of O_2 or their relevance to oneself (discussed primarily in this chapter).

Being ignorant of procedural and personal limitations (covered throughout this manual).

6.1 Common Oxygen Parameters

3.0 - Hyperbaric use

1.6 - Max exposure for divers at rest

1.4 - Max recommended exposure for moving diver

.5 – PPO_2 at which pulmonary toxicity is a concern

.22 - Hyperoxic (more than 21% oxygen)

.20 - Hypoxic (less than 21% oxygen)

.16 - Hypoxic danger zone

.10 - Unconsciousness and death become very likely

6.2 Oxygen: How Much is Enough?

Perhaps the biggest confusion surrounding oxygen breathing concerns the significant variability with respect to oxygen tolerance between individuals and within one individual over time. For example, on certain days, one individual may go for several hours on a given oxygen dose, but experience toxicity with half this dose on another day. Literally thousands of hours of research form the basis of commonly accepted oxygen limits, yet these limits remain imprecise. It is very unlikely that researchers will ever be able to establish the exact limits of a given exposure to oxygen, but the current ranges, being quite conservative, appear effective at insulating divers from the imprecise measure and high variability of oxygen tolerance. There are several reasons why it is very difficult to establish the precise limits to oxygen exposure; these include:

High degree of variability in oxygen tolerance

Inconsistent measurements and difficulty assessing actual oxygen effect

Poor understanding of oxygen toxicity mechanisms

When researchers plot the results of given oxygen doses (usually measured as PO_2 for a given time), the results are highly inconsistent. Tolerances often vary so dramatically that no notable trend in tolerance can be established, i.e. increased or decreased. As Kenneth Donald observed, "the most striking finding was the enormous variation in oxygen tolerance in a group of human beings. Exposures, causing marked symptoms at this tension, varied from 6 to 96 minutes in a group of 37 individuals."[1]

Most oxygen tolerance testing was done with pure oxygen at 30ft (9m), 60ft (18m), and 90ft (27m). To ensure safety in the event of a toxic seizure, this testing was usually done in dry chambers with support personnel present. During these tests, many individuals managed amazing tolerances while others experienced problems very early in the tolerance time limits. To complicate matters, some individuals managed very short exposures on one day and lengthy exposures on another. The consequence of these variations was that measuring true oxygen tolerance proved to be a significant problem.

Early tests often used time limits based upon actual toxic events (i.e. seizures), while later studies used time limits based on what have commonly become recognized as symptoms. As a result, some individuals who managed significant times when pushed to seizure were then limited, perhaps prematurely, by the occurrence of a symptom. At least loosely, symptoms did seem to relate to toxicity incidence; however, the relation was unreliable and fraught with complications. This difficulty in establishing a consistent and reliable measure of toxic reactions further skews what one might refer to as the "actual" toxicity time limit (if there is such a thing).

This inability to objectively assess the mechanisms of oxygen toxicity undermines our ability to understand the process, and limits the degree to which we can track its development. For example, numerous factors (e.g. in-water immersion) increase the risk of oxygen toxicity, but our imprecise understanding of the mechanisms of oxygen toxicity limits our ability to plot and control the many variables that impact on it. However, as our understanding of oxygen toxicity grows, we seem to be closer to appreciating its primary mechanics, and perhaps to granting divers a greater degree of safety.

6.3 What is Oxygen Toxicity?

Elevated oxygen pressures affect the whole body. Their impact can accumulate, expressing itself most notably as seizure or lung damage. While both of these reactions are exceedingly uncommon, they are possible responses to excessive or irresponsible oxygen doses. In diving, by far the most common cause of oxygen toxicity is the careless use of oxygen-rich mixtures.

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1 Donald, K. (1992) *Oxygen and the Diver.* Worcs., Great Britain: The SPA Ltd.

6.3.1 Central Nervous System Oxygen Toxicity

CNS toxicity appears to result from the accumulation of elevated partial pressures of oxygen (usually 1.4 PO_2 and, more typically, 1.6 and beyond). These levels seem to precipitate a reaction in which an epileptic-like seizure is induced in the victim, causing violent full-body spasms. In the diving victim, this reaction will often result in the loss of the regulator, resulting in drowning. *Central nervous system oxygen toxicity (CNS toxicity)* is also sometimes referred to as the *Paul Bert effect*, after the researcher who first described it. CNS toxicity is by far the most relevant to divers since it can be triggered quickly (in a matter of minutes) with high oxygen exposures (high partial pressures of around 1.6 and beyond). Theoretically, CNS toxicity risk is also present with the cumulative use of oxygen over the course of several hours or even among repetitive dives. There is little evidence of accumulated oxygen in this lower range inducing CNS toxicity, but it seems possible that accumulated oxygen doses can make one susceptible to toxicity, and may result in toxicity in seemingly unjustifiable situations with relatively lower oxygen exposures. Due to the substantial risk of such reactions, i.e. death, it is very wise to carefully manage oxygen exposure and to avoid pushing oxygen limits

6.3.2 Pulmonary or Whole Body Oxygen Toxicity

CNS toxicity is by far the most common risk to divers, but elevated oxygen doses also affect the diver's whole body. *Pulmonary oxygen toxicity* appears to be the result of prolonged exposures to elevated oxygen content, and is usually evident as lung irritation or breathing discomfort. This affliction can progress to a fatal condition during extremely long exposures, usually on the order of many days, or with very long repetitive dive exposures over the course of weeks. The exposures necessary for serious lung damage are SIGNIFICANT, and very unlikely in nearly all diving. However, very long technical diving excursions or even moderate exposures can impact at least short term lung health, and likely degrade decompression efficiency when not properly managed. Pulmonary toxicity is much less of a relevant risk than CNS toxicity for the vast majority of divers, but is nonetheless another of many very impotant reasons to carefully limit elevated oxygen exposure. Pulmonary toxicity is covered in more detail later in this section.

6.3.3 Symptoms of CNS Oxygen Toxicity

Historically, people have focused too much attention on the symptoms associated with CNS toxicity, leading some to believe that these symptoms can be used as a way of anticipating a toxic event. Actually, there may be no symptoms prior to CNS toxicity, and some symptoms can easily go unnoticed. If one notices CNS symptoms, one should inform one's dive partner and immediately switch to a lower oxygen mixture and/or ascend. One should never struggle or kick in such a situation, as the CO_2 increase may increase one's susceptibility. The symptoms of oxygen toxicity include, but are not limited to, the following:

Nausea/vomiting	Constriction of visual field	Lip twitching
Light-headedness	Facial Pallor	Pupil Dilation
Dizziness	Sweating	Muscle Twitching
Vertigo	Bradycardia	Tingling
Retrograde amnesia	Illusions	Hallucinations
Confusion		

The acronym **CONVENTID** has been used as a simple way to remember the most common symptoms:

Con(vulsion) = may strike without any of the following symptoms

V(isual disturbance) = splotchy or tunnel vision, reddish dots/field etc.

E(ars) = auditory disturbance or euphoria

N(ausea) = self explanatory

T(witching) = muscle spasms, i.e. eye twitching or tingling (muscles/skin)

I(rritability) = self explanatory

D(izziness) = self explanatory

The following chart indicates the variation of tolerance of individual divers to oxygen toxicity at

TABLE 6.1 PERCENTAGE OF DIVERS EXHIBITING SYMPTOMS OF OXYGEN TOXICITY

Depth	Time limit	Number of divers	Number of divers convulsing	Time to onset of convulsions	Number/ percentage without symptoms
50	120	40	16	12 to 69	3 (7%)
40	120	29	4	12 to 28	14 (48%)
35	180	21	1	30	15
30	120	20	2	43 to 48	17
25	120	29	0	0	28

50ft and 70ft while underwater at rest. Note the various symptoms and the high percentage of subjects without any symptoms. It is crucial to note that there may be no symptoms of oxygen toxicity before the onset of a toxic event.

TABLE 6.2 VARIATIONS OF TOLERANCE TO OXYGEN TOXICITY[2]

NAME	TIME (mins)	DEPTH (fsw)	SYMPTOMS	DAY IN SERIES
Gibson Av. Time 36 Variation 10-100	12 100 23 10	50 50 50 50	Convulsed No symptom Convulsed Lip twitching	1 17 23 28
Gray Av. Time 26 Variation 10-29	10 29 25 21 28	50 50 50 50 50	Severe lip twitching Slight lip twitching, body tremors Severe lip twitching Lip twitching Lip twitching, convulsed	1 7 14 18 21
Knight Av. Time 27 Variation 17-39	17 32 24 21 39	50 50 50 50 50	Lip twitching, body tremors Nausea and lip twitching Lip twitching Nausea, lip twitching Severe lip twitching	1 5 15 20 22
McInnes Av. Time 38 Variation 19-100	19 100 29 20 19	50 50 50 50 50	Lip twitching No symptoms Lip twitching Lip twitching Lip twitching	1 6 7 13 14
McLaughlin Av. Time 30 Variation 16-53	24 53 16 27	50 50 50 50	Lip twitching, convulsed Lip twitching Lip twitching Lip twitching	1 9 17 21
Murton Av. Time 37 Variation 14-102	102 20 14 22	50 50 50 50	Severe nausea Headache Lip twitching Lip twitching	1 5 10 12
Shields Av. Time 41 Variation 20-69	51 69 20 24	50 50 50 50	Severe lip twitching Convulsed Lip twitching Lip twitching	1 3 8 10
Witham Av. Time 19 Variation 14-26	15 26 16 14 23	50 50 50 50 50	Convulsed Lip twitching Lip twitching Lip twitching Lip twitching	1 21 24 29
Miller Av. Time 49 Variation 32-68	36 68 51 44 43 32	70 70 70 70 70 70	Lip twitching Lip twitching Lip twitching Nausea Retrosternal pain and Malaise Convulsed	1 4 7 13 15 28
Herrett Av. Time 26 Variation 7-52	36 52 26 20 18 7 36 16	70 70 70 70 70 70 70 70	Lip twitching Lip twitching Lip twitching Convulsed Lip twitching Lip twitching Nausea Paraesthesia	1 6 8 12 14 19 27 33

2 Donald, K. (1992) *Oxygen and the Diver* p 48. Worcs., Great Britain: The SPA Ltd.

Kenneth Donald writes, "There are great variations in the resistance of the individual to the general background of intoxication and in the resistance of the individual to the convulsant factor. Again, certain individuals may show powerful convulsive movements, either localized or generalized, but retain consciousness. Others pass into what is indistinguishable from an epileptic fit immediately after such convulsive movements and, occasionally, in their complete absence."[3]

Thus, Kenneth Donald observes, "it becomes clear that to judge even a single man's tolerance by one or even several dives is dangerous and unjustifiable. If we examine the performances of the three divers who survived for 100 minutes at 50 feet, we find that the averages of all their other performances at this depth are 22, 19 and 15 minutes respectively. One of the most striking cases is that of Gibson who convulsed after 12 minutes at 50 feet 16 days later he completed 100 minutes without symptoms. Six days after this he again convulsed after 32 minutes. Such findings as this make it clear that to dive on oxygen *to any toxic pressure involves a risk that is impossible to assess.*" [4]

TABLE 6.3 VARIATIONS AMONG INDIVIDUAL DIVERS[5]

Depth in Water	50 FEET	60 FEET	70 FEET	80FEET	90 FEET	100 FEET
Kirk	35	2	1.5	3	2	2.5
Mulberry	11	15	4	4.5	4	3
Wallis	99	24.5	10.5	8.5	4	3
Robertson	35.5	19.5	11	9.5	11.5	4
Ward	35	8	38	13	7.5	3.25
Sims	26.5	13	12	13	9.5	7.5
McAtamney	35.5	16	39	18	9	5
Brown	44.5	19	14	35.5	12	11.5
Rogers	90	37	26	27.5	11.5	7.5
Whittington	59.5	73.5	19.5	8	11	12.25
Dickie	121	12.5	55	28	9.5	24.75
Smith	85	80	43.35	13	71	7.5
Fraser	120	37.5	74	44.5	18.5	19
Derrick	90	40	77.5	20	38	36.5
Geometric Mean	54.00	20.17	19.56	13.72	10.39	7.41
Logarithm of Mean	1.7324	1.3047	1.2913	1.1373	1.0165	0.8698

The preceeding table represents an attempt to estimate the degree of variability of the individual divers. The logarithm of the mean value for each depth is subtracted from the diver's time. The resulting figure shows the diver's inferiority, or superiority, to the average of each depth. The variability of each diver can thus be calculated assuming that his deviation from the mean is independent of the depth. On this assumption, only 40 percent of the total variance of oxygen divers is accounted for by the day-to-day variation of each individual diver. The other 60 percent is due to variation between the averages of different divers.

6.4 Off Effect

The *off effect* is a well-known effect apparently caused by returning to air-breathing after being exposed to toxic tensions of carbon dioxide. It is characterized by a sudden worsening of symptoms; i.e. headache, nausea, and vomiting. An off effect is also known to occur after ceasing to breathe oxygen at toxic tensions. However, it is not as frequent as when one stops breathing carbon dioxide, where in some cases, it appears that reverting to air breathing may have caused convulsions. Some claim that these convulsions were inevitable because an overwhelming degree of toxicity had already been reached.

As a result of Dickens' work[6], we know that brain tissue respiration is impaired by high tensions of oxygen. It is possible, then, that nerve cells are "eliminated" individually, and that they show a distribution of oxygen tolerance very similar to that which exists across a group of men. Certain cells, whose elimination may cause symptoms or convulsions, could be activated by the sudden reduction of oxygen tension, further reducing metabolism in these damaged cells. Furthermore, it would seem that the switch to air breathing increases gas density, CO_2 accumulation, blood pH, and catecholamine production, compounding the likelihood of toxic episodes.

6.5 Why Do We Get Oxygen Toxicity? (Paul Bert Effect)

Oxygen has an effect on the regulation of blood flow, tissue oxygenation, and energy metabolism in the brain, as well as on many other body functions. These effects are pressure-dependent and are involved in the development of toxicity. The exact mechanism is uncertain, but the following information serves to provide a general outline for responsible oxygen use:

Oxygen Use Outline

I. Early focus on neurotransmitter interference

- A. Gamma-aminobutyric acid (GABA)
    1. Primary inhibitory neurotransmitter in brain
    2. Limits neural activity
    3. Decreases with increased hyperoxia

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3 Donald, K. (1992) *Oxygen and the Diver.* Worcs., Great Britain: The SPA Ltd.
4 Donald, K. (1992) *Oxygen and the Diver.* Worcs., Great Britain: The SPA Ltd.
5 Divers are resting on oxygen at testing depth in fsw. Time is in minutes.
6 Donald, K. (1992) *Oxygen and the Diver,* p. 62. Worcs., Great Britain: The SPA Ltd.

B. GABA is no longer thought to play a role in hyperoxic seizures

1. GABA decreases with hyperoxia but seizures not inevitable

2. Seizures occur without change in brain GABA

II. Reactive Oxygen Species (ROS): Current thought for CNS toxicity

A. ROS are toxic by-products of cellular oxidative metabolism

1. Blamed for a number of degenerative processes, i.e. aging

2. Oxygen free radicals are ROS- unpaired electron in outer shell

3. H_2O_2 (Hydrogen Peroxide) is a product of radical chemistry

a. It is not a free radical but is a ROS and toxic

b. It can diffuse out of cells and react with other cells

III. Hyperoxic exposure and cellular metabolism

A. Oxygen is consumed to produce adenosine triphosphate (ATP)

B. ATP (stored form of energy) production allows free electrons to combine with oxygen to form a superoxide radical

C. Superoxide formation is common, and body defends with super oxide dimutase (SOD)

D. SOD converts superoxide into H_2O_2 (hydrogen peroxide) that can be toxic, and possibly an important link in hyperoxic seizures

E. Enzymes like glutathione peroxide detoxify H_2O_2

F. Detoxification of H_2O_2 requires reduced glutathione (GSH)

G. Addition of GSH increases time to seizure, implying that increased levels of H_2O_2 may help trigger seizures

H. During hyperoxia (3.0 PO_2), H_2O_2 can increase by up to 700%

IV. Hydrogen Peroxide accumulation

A. Superoxide conversion and other enzymes create H_2O_2

B. Monoamine oxidase (MAO) converts catecholamines like epinephrine, norpinephrine/ adrenaline or noradrenaline into H_2O_2

C. Drugs that inhibit MAO delay onset of seizures, indicating that catecholamine levels may lead to increased production of H_2O_2 that may cause a hyperoxic seizure

D. Catecholamine levels vary naturally, i.e. with sleep cycle, and greatest tolerance to hyperoxic seizures occurs when these levels are lowest

V. Development of CNS toxicity

A. Mechanisms not understood, but some good clues

B. H_2O_2 is not particularly reactive, but can be reduced to hydroxyl radical, which is very reactive and toxic

C. H_2O_2 accumulation seems well-linked to hyperoxic seizures

A. Hypercapnia (CO_2 accumulation) has long been known to accelerate the onset of hyperoxic seizures

1. CO_2 is a powerful vasodilator, but it is not clear whether this actually increases brain O_2 or whether levels of brain O_2 actually impact seizures, as they typically occur at less than ½ peak levels

2. It may be that actual CO_2 levels activate sympathetic nervous system, releasing catecholamines, which are metabolized by MAO to H_2O_2, leading to a seizure

3. CO_2 accumulation may arise from poor regulator performance, poor fitness, heavy exertion, or gas density

B. Some drugs may elevate catecholamines and increase risk

1. Pseudoephedrine (decongestant) causes release of catecholamines that are metabolized by MAO and converted to H_2O_2

2. Epinephrine, norepinephrine/adrenaline or noradrenaline are all catecholamines and may produce excess H_2O_2

C. Stress activates sympathetic nervous system, releasing catecholamines and potentially contributing to seizure

1. Thermal stress, either hypothermia or hyperthermia

2. Physical exertion

3. Fatigue or lack of sleep

4. Dehydration

VII. Avoidance of CNS Toxicity

A. Maintain reasonable PO_2 <1.4 for dive, PO_2 <1.6 for decompression

B. Track CNS exposure via percentage of allowable 100%

C. When doing O_2 deco or CNS % > 75%, switch from high oxygen gas to lower oxygen gas. This is commonly known as a *break*.

D. Limit exertion, CNS buildup, and thermal stress

E. Avoid drugs or alcohol

F. Maintain hydration

Chapter 7

Avoiding Oxygen Toxicity

7.0 Introduction

A great deal of debate surrounds the mechanics of oxygen toxicity and the symptoms that indicate an approaching attack. Much of the information presented here is designed to afford divers the ability to make educated decisions and responsible choices. Nonetheless, it may also benefit a small number of very aggressive underwater explorers who are pioneering an expanded understanding of oxygen tolerance. Most divers will find that by following several very simple guidelines, they will limit themselves to responsible oxygen exposures that are perfectly sufficient for their operational needs.

7.1 Toxicity Limits

The following guidelines are widely accepted as conservative limits as originally published by NOAA. Nonetheless, individuals should always remember that oxygen limits are imprecise. During testing, while many individuals managed amazing tolerances, others experienced problems very early in the tolerance time limits, and, to complicate matters, others managed very short exposures on one day, and lengthy exposures on another. Furthermore, elevated CNS percentages become more problematic when combined with contributing factors like work, water temperature, CO_2 accumulation, immersion in water, drugs, and fatigue. It is good to remember that susceptibility to oxygen toxicity is a very personal affair.

Unfortunately a great deal of emphasis has focused on oxygen toxicity limits, leaving individuals with the sense that precise measures exist for tracking and measuring risk of oxygen toxicity. In truth these limits are guidelines, generally outlining zones of increasing risk. Very little risk appears in the lower range below 1.4 PO_2 and most responsible divers maintain a careful approach to elevated oxygen mixtures above this range.

While diving, most individuals will have little trouble maintaining a low level of risk with respect to oxygen exposure. Divers need merely adjust the oxygen mixture downward with longer dives while always maintaining a good margin for error. For example, GUE standard diving mixes prescribe a maximum PO_2 of 1.3 with variation for increased effort, stress, or environmental conditions.

A PO_2 of 1.4 is the maximum recommended for a diver under stress, while a PO_2 of 1.6 is the absolute maximum permissible, and usually reserved for a resting diver during decompression. Oxygen tolerance is highly variable and can be altered by many factors, including physical condition, cumulative exposure, immersion, exertion, and water temperature. Tracking the effect of one or multiple exposures involves

TABLE 7.1 CNS TOXICITY LIMITS FOR DIVING EXPOSURES

PO_2	Single Exposure (Mininutes)	Maximum (24-Hour Day)
1.4	150	180
1.3	180	210
1.2	210	240
1.1	240	270
1.0	300	300
0.9	360	360
0.8	450	450
0.7	570	570
0.6	720	720

calculating the time spent at a given PO_2 and relating it to the recommended limits. The time spent at this PO_2 is described as a percentage of the total available time, also known as the *oxygen clock*.

The upper oxygen range beyond 1.4 PO_2 is reserved for experienced divers conducting decompression dives and therefore able to "break" (stop breathing the high oxygen mix for periods of time) from the elevated oxygen to lower oxygen mixtures. Use of oxygen mixtures approaching 1.6 PO2 should be done only where "breaks" are feasible and divers can control exertion level and stress while having access to

TABLE 7.2 CNS TOXICITY LIMITS FOR DECOMPRESSION MIXTURES

PO^2	Single Exposure (Min.)	Maximum (24-Hour Day)
1.6	45	150
1.5	120	180

lower oxygen mixtures to allow for alternating cycles of low oxygen breathing.

Understanding the potential variability in oxygen tolerance is important not only when considering oxygen toxicity but also when discussing the oxygen clock. This hypothetical clock works by relating the chosen maximum time at a given PO_2 (i.e. 45min at 1.6) to a percentage of accumulated time at this

PO_2. Of course, the success or failure of this clock depends on the accuracy of the time limit; a limit made ambiguous by susceptibility. The 100% limit (i.e. 45min at 1.6) suggests that to go beyond this limit markedly increases one's risk of oxygen toxicity. Nonetheless, GUE and WKPP exploration divers regularly exceed several thousand percent, highlighting the substantial variation that exists within oxygen limits. This variation can be explained either by the effective procedures and individual physiologies at work in these dives, or it may represent the failing of the conceptual model of oxygen used in this context. Most likely, it suggests something in between.

Oxygen toxicity measurements can best be seen as general rules of thumb. They are the diving community's "best guesses" regarding oxygen limits, limits based on highly variable and conflicting data. Objectively, these limits are probably overly conservative for the vast majority, good for some, and not good enough for a very few. However, given the risk posed by oxygen toxicity (i.e. seizure and likely drowning), it is best that most divers stay near the limits. Nonetheless, these "limits" should not be seen as absolute, but rather as a range that should be used as generally sensible guidelines.

Ardent belief that these "limits" are absolute has generated its own set of problems in technical diving, leading some to assume that they must shave an extra 5% or 10% off their clock by using odd gas mixtures. Using odd gas mixes designed to shave exposure from a somewhat arbitrary limit often creates more problems then it solves. Divers are likely best served by regular breaks from oxygen (for both decompression benefit and extended O_2 tolerance) and the conservative use of PO_2 (such as 1.4 or less for diving). Careless oxygen use can be fatal; therefore, for most divers, aggressive oxygen exposure is not worthwhile. Furthermore, it is important that divers carry out regular break cycles (going off oxygen), particularly on long dives where there is significant oxygen accumulation. While a number of different break cycles are successful, most divers breathe oxygen for 20 minutes, then follow it with a 5-minute break on a mixture with reduced oxygen content (historically air but more sensibly a breathable Trimix mixture). Divers with only 20 or 30 minutes of total decompression can insert the break in the middle of their decompression to derive maximum benefit from the break.

7.2 The CNS Clock

The premise of the oxygen clock is entirely theoretical as it relates to established data, which is itself generally unreliable. It is clear that commonly recognized limits are a good measure of general resistance to oxygen toxicity. Yet, these limits and their associated manipulations (such as the oxygen clock) are at best imprecise and at worst misleading and dangerous.

For example, exceedingly few divers will ever experience oxygen toxicity while following these limitations. Yet, as with decompression tables and most physiological events there are no guarantees about a divers resistance to oxygen toxicity while within established limits. This makes it essential that divers understand the spirit of oxygen toxicity risk, identifying the most prominent areas of increased danger. With respect to oxygen toxicity these risks are most obvious to oxygen exposures that approach and exceed 1.6 PO2.

Very little risk appears in the lower range below 1.4 PO2 and most responsible divers maintain a careful approach to elevated oxygen mixtures above this range. Realistically the upper oxygen range beyond 1.4 PO2 is reserved for experienced divers conducting decompression dives and therefore able to "break" (stop breathing the high oxygen mix for periods of time) from the elevated oxygen to lower oxygen mixtures. Use of oxygen mixtures approaching 1.6 PO2 should be done only where "breaks" are feasible and divers can control exertion level and stress while having access to lower oxygen mixtures to allow for alternating cycles of low oxygen breathing.

As a theoretical tool the concept of the oxygen clock can help divers estimate accumulating risk. It should be obvious that as divers increase the level of oxygen, the recommended limiting time decreases and there are fewer margins for error. There is also a growing level of risk associated with relatively minor changes in time of exposure. Calculating oxygen clock exposures is largely a theoretical tool for planning decompression exposures. It is presented below for illustrative purposes and followed later in the chapter by additional comments on oxygen planning.

Generally speaking it is sufficient in most situations to ensure that divers are safely below prescribed oxygen limits outlined above and that any decompression mixes utilize oxygen breaks (periodic breathing of lower oxygen mixes such as 20 minutes on high oxygen and five on lower oxygen mixture) as discussed in later sections.

Divers spend 30min at 90fsw (27msw) with a 36% Nitrox mix. What percentage of their theoretical CNS clock did they use up? Divers are at 2.72 ATA + 1 (surface) X .36 (% Nitrox) = 1.4 $P0_2$. NOAA limits divers to 150 minutes at a PO_2 of 1.4. Given that the team has spent only 30 of 150 available minutes at this PO_2, it leaves them with 30 / 150 or 20%. Excluding any decompression, the divers have only used up 20% of their CNS clock.

Decompression obligation, of course, changes things. Generally, divers should not exceed 100% CNS on any given dive. Most divers find this recommendation easy to follow, but as decompression obligations grow, CNS accumulation becomes significant. For example, **divers spend 60min at 100ft (30m) with a 32% Nitrox mix, and have a decompression obligation of 1min at 40ft (12m), 4min at 40ft (9m), 11min at 20ft (6m); the last they would like to do on 100% oxygen**. The resultant total CNS here is 60% (dive CNS = 34%; decompression CNS= 26%). Here we see that whereas the dive accounts for more than 30% CNS, the decompression accounts for a nearly the same CNS loading. In the case of longer dives, particularly deeper ones with greater decompressions, there is more CNS loading.

7.2.1 Rethinking the Oxygen Clock

Numerous examples demonstrate that there is a time function associated with oxygen toxicity. For example, divers breathing excessive pressures (greater than 10 ATA) of oxygen for very short periods of time may not develop toxic reactions. Alternatively, they may experience toxic reactions after only several breaths. Generally speaking the greater the PO2 the sooner the toxic reaction.

Wide variation among and within individuals greatly clouds the issue of precise measurement as it applies to toxic reactions. The *clock model* discussed above suggests that one's chances of convulsing steadily increase over time as the duration of the exposure increases. However, very little research has studied CNS toxicity at low PO_2 (around 1.0 to 1.4). Some speculate that divers could breathe low oxygen doses (below roughly 1.4) forever and not experience an oxygen seizure (though in this case pulmonary toxicity would be a limiting factor). This *threshold model* assumes that as long as a diver is below the threshold PO_2 (undefined and unproven), then s/he would not be vulnerable to toxicity. Conversely, the clock model assumes that the cumulative exposure would predispose one (with individual variation) to a toxic reaction.

Oxygen testing data is often so inconclusive as to make final determinations very difficult. While evidence exists to support either the clock or threshold model (for CNS toxicity), some exposures seem to clearly outline a cumulative oxygen component. For example, studies evaluating a diver's ability to sustain high PO_2 interspaced with lowered PO_2 exposures, indicated a notable accumulation of oxygen

1 Case, E.M. & Haldane, J.B.S. (1941) Human physiology under high pressure. *J. Hyg. Camb*. **41**, 225-249.

toxicity risk that resulted in seizure while under reduced PO_2.[1] In contrast, pulmonary toxicity certainly has both clock and recovery components.

7.3 Pulomary Toxicity (Lorraine Smith Effect)

Pulmonary toxicity was first described by researcher Lorraine Smith, and is the result of an accumulated exposure to elevated oxygen levels. Smith described a patient who died of lethal pneumonia after being exposed to 73% oxygen mixture for four days, calling the ailment *pulmonary oxygen toxicity*. While it can be lethal, pulmonary oxygen toxicity is often ignored by many diving texts since it is exceedingly uncommon in the diving community. Symptoms of pulmonary toxicity include chest tightness, cough, chest pain, shortness of breath, and reduction in vital capacity. Assuming that they limit themselves to the common guidelines, the vast majority of Nitrox divers need not be concerned about pulmonary toxicity. While this form of toxicity is most easily and commonly localized in the lungs, researcher Bill Hamilton coined the term *Whole Body Toxicity* to indicate the more comprehensive damage associated with elevated oxygen exposures. Both terms describe the same ailment.

7.3.1 Oxygen Toxicity Impact on Lung Function

While Whole Body Toxicity is a more appropriate term for the accumulation of toxicity in the body, it remains customary to refer to this toxic accumulation as Pulmonary Toxicity. The most likely reason for this focus on the pulmonary system is that it can be more easily quantified and measured. In fact, lung vital capacity is the most consistent and widely used indicator of pulmonary toxicity.

Vital capacity is essentially a measure of mechanical lung function, which is measured with a spirometer. During testing, individuals take a deep breath and blow deeply into a spirometer, which calculates expiration force and lung volume. With advancing toxicity, lung function generally becomes reduced, meaning that the lungs are unable to hold as much air, nor expel it with the same force. Research indicates that gas exchange function is impaired less severely and later than is pulmonary mechanical function; interestingly, pulmonary diffusing capacity for carbon monoxide seems to be a far more sensitive measure of pulmonary recovery (Clark et al 1987; Clark 188a). The reduction in pulmonary diffusing capacity is likely a key element to the efficiency of oxygen break cycles with respect to decompression efficiency (covered in more detail in the section on decompression).

7.3.2 Tracking Pulmonary Oxygen Toxicity

To effectively track oxygen exposure, researchers needed a uniform measure of oxygen dose. The *Unit Pulmonary Toxicity Dose* (UPTD) was chosen to express any pulmonary toxic dose in terms of an equivalent exposure to oxygen at 1.0 ATA. Over the years, a good degree of misunderstanding has accumulated, with people confusing UPTD with CPTD *(Cumulative Pulmonary Toxicity Dose)* and OTU (*Oxygen Tolerance Unit*, coined by Bill Hamilton as part of the Whole Body Toxicity paradigm). These units all measure a standard reference level of hyperoxia, but vary slightly in how they present the data. Because of this, most people wrongly assume they track different parameters. Presentation is the only practical difference between the common terms UPTD and OTU, as we will illustrate below.

Established oxygen limits must account for both the actual oxygen exposure a diver is subject to during permanent lung damage. Thus, it is unwise to risk reductions that exceed roughly 4%. Divers should bear in mind that on long dives with excessive oxygen exposure, DCI could require recompression, subjecting one to additional unplanned levels of oxygen exposure. Vital capacity reductions in the 2% to 4% range allow for a margin of error in the case of decompression accidents.

While UPTD parameters list vital capacity measurements that reflect the rate of pulmonary impact, OTU charts attempt to model similar parameters but suggest a daily and total dose limit, making them easier for multi-day use. The formula for calculating UPTD/OTU units is as follows: $t(PO_2 - .5/.5)^{.83}$. The Hamilton Repex method utilizes the same UPTD research data and suggests limits that approximate a 4% reduction in vital capacity as a maximum single-day exposure limit. Furthermore, the Repex method reduces the daily allowable exposure with cumulative oxygen dose.

Assume, now, that the same two dives were repeated the following day. Under normal conditions, the second round of dives would accumulate an additional 231 OTU's. However, after 24 hours, previous dives no longer count against the accumulated total. Nonetheless, progressive oxygen exposure has been shown to promote lung damage. Therefore, the OTU chart accounts for additive effect by reducing total allowable OTU units.

The primary goal of parameters such as UPTD and OTU limits is to establish safe levels of oxygen exposure. Several equations have attempted to predict vital capacity levels based on time and PO_2 as they relate to existing test data. One example of this is Harabin et al's equation: $\%\Delta VC = -.011(PO_2 - .5)\ t$,[4] where $\%\Delta VC$= % change in vital capacity and t= time at PO_2. Essentially statistical tools, these equations are used mainly to test the overall consistency of available data.

TABLE 7.3 EQUIVALENT UPTD VALUES AND AVERAGE DECREMENTS IN VITAL CAPACITY [2]

Equivalent UPTD Units	Average Percent Decrement in Vital Capacity
615	2
825	4
1035	6
1230	8
1425	10
1815	15
2190	20

2 Table 7.2 - Adapted from Wright 1972

In light of the preceeding chart, the 615 UPTD dose would be equivalent to approximately a 2% reduction in vital capacity. This exposure would probably involve only mild symptoms and would be completely reversible. However, a UPTD of 1425 would entail a 10% reduction and would likely be permissible only in the more extreme cases of severe recompression treatment. Though people have recovered from vital capacity reductions as high as 45%, they could also have easily been left with permanent lung damage. Thus, it is unwise to risk reductions that exceed roughly 4%. Divers should bear in mind that on long dives with excessive oxygen exposure, DCI could require recompression, subjecting one to additional unplanned levels of oxygen exposure. Vital capacity reductions in the 2% to 4% range allow for a margin of error in the case of decompression accidents.

While UPTD parameters list vital capacity measurements that reflect the rate of pulmonary impact, OTU charts attempt to model similar parameters but suggest a daily and total dose limit, making them easier for multi-day use. The formula for calculating UPTD/OTU units is as follows: $t(PO_2 - .5/.5)^{.83}$. The Hamilton Repex method utilizes the same UPTD research data and suggests limits that approximate a 4% reduction in vital capacity as a maximum single-day exposure limit. Furthermore, the Repex method reduces the daily allowable exposure with cumulative oxygen dose.

Example 1

A dive conducted with a PO_2 of 1.4 for 45 minutes would yield:

1.63 OTU's per minute x 45 minutes = 73.35 total OTU's.

Similar to accounting for residual nitrogen when calculating decompression tables, when tracking the accumulation of whole body oxygen toxicity units, the count resets every 24 hours. Therefore, with respect to pulmonary recovery, after 24 hours, a particular exposure no longer counts against the accumulated total.

Example 2

The above dive followed by another dive to a PO_2 of 1.2 for 120 minutes would yield:

73.35 OTU's + (1.32 OTU's per minute x 120 minutes or 158 OTU's) = 231 total OTU's.

Assume, now, that the same two dives were repeated the following day. Under normal conditions, the second round of dives would accumulate an additional 231 OTU's. However, after 24 hours, previous dives no longer count against the accumulated total. Nonetheless, progressive oxygen exposure has been shown to promote lung damage. Therefore, the OTU chart accounts for additive effect by reducing total allowable OTU units.

The primary goal of parameters such as UPTD and OTU limits is to establish safe levels of oxygen exposure. Several equations have attempted to predict vital capacity levels based on time and PO_2 as they relate to existing test data. One example of this is Harabin et al's equation: $\%\Delta VC=-.011(PO_2-.5)t$, [3] where $\%\Delta VC$=% change in vital capacity and t+ time at PO_2. Essentially statistical tools, these equations are used mainly to test the overall consistency of available data.

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3 CLARK, J. M. (1993) Oxygen Toxicity. In *The Physiology and Medicine of Diving,* 4th edn, p. 7 . Ed. P. Bennett, & D. Elliott. London: W. B. Saunders Co. Ltd.

TABLE 7.4 OTU/UPTD's PER MINUTE [4]

OTU/UPTD Table t ((PO_2 - .5) / .5) .83	
PO2	OTUs/per Min
0.6	0.27
0.7	0.47
0.8	0.65
0.9	0.83
1.0	1.0
1.1	1.16
1.2	1.32
1.3	1.49
1.4	1.63
1.5	1.78
1.6	1.93
1.7	2.07
1.8	2.21
1.9	2.35
2.0	2.49

4 Test subjects have shown no significant vital capacity reduction with PO_2's less than .5, indicating that only higher PO_2 levels are significant (thus the PO_2 - .5 in Harabin's formula).

TABLE 7.5 OTU CHART: HAMILTON REPEX METHOD [5]

Exposure (mission duration, in days)	Average Daily Dose	Total Mission Limits
1	850	850
2	700	1400
3	620	1860
4	525	2100
5	460	2300
6	380	2520
7	350	2660
8	330	2800
9	310	2970
10	300	3100
11	300	3300
12	300	3600
13	300	3900
14	300	4200
15-30	300	As required

5 OTU chart reprinted from Hamilton's Repex Method. Note that the acceptable exposure is reduced with multi-day oxygen use.

more relevant calculation of common and extreme dives

E. Protection from Whole Body Toxicity

Dr. James Clark at the University of Pennsylvania discovered that oxygen breaks led to more than a doubling of a diver's resistance

7.4 Review of Key Points Relevant to Whole Body Toxicity

A. Pulmonary or Whole Body Oxygen Toxicity

Discovered by Lorraine Smith

Cumulative effect of hyperoxic exposure (>.5PO_2)

Effects whole body, but greatest and most measurable impact is to the lungs

Is not commonly a problem in any but the most severe exposures

B. Symptoms

Chest tightness

Cough

Chest pain

Shortness of breath

Reduction in vital capacity can be measure via spirometer or estimated through Harabin Equation %VC drop= $- .011(PO_2 - .5)\ t$

C. Whole body toxicity tracking

Unit Pulmonary Toxicity Dose (UPTD) or Cumulative Pulmonary Toxicity Dose (CPTD) developed at University of Pennsylvania

These units and the later Oxygen Tolerance Unit (Bill Hamilton) represent one minute of pure oxygen consumption at the surface

$OTU = t(PO_2 - .5 / .5)^{.83}$ where t = time at PO_2

D. Whole Body Toxicity manifestations

Most measurable through lung function; i.e. vital capacity

Greater reduction in vital capacity (VC) indicates more severe impact and longer recovery

Opinion varies, but 2% reduction in VC is considered acceptable

Greater than 10% reduction in VC is considered justifiable only in extreme situations and may cause permanent damage, therefore VC reduction during diving must allow for Hyperbaric Oxygen Therapy

Single day dosage limits are very hard to reach, but as time progresses the risk becomes a more relevant calculation of common and extreme dives

E. Protection from Whole Body Toxicity

Dr. James Clark at the University of Pennsylvania discovered that oxygen breaks led to more

TABLE 7.6 UNITS PULMONARY TOXICITY DOSE (UPTD) FOR GIVEN PO_2

	PO_2										
Minutes	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
1	0.26	0.47	0.65	0.83	1.00	1.16	1.32	1.48	1.63	1.78	1.92
2	0.53	0.93	1.31	1.66	2.00	2.33	2.64	2.95	3.26	3.56	3.85
3	0.78	1.40	1.96	2.49	3.00	3.49	3.97	4.43	4.89	5.33	5.77
4	1.05	1.87	2.62	3.32	4.00	4.65	5.29	5.91	6.52	7.11	7.70
5	1.31	2.34	3.27	4.15	5.00	5.82	6.61	7.39	8.14	8.89	9.62
6	1.58	2.80	3.93	4.99	6.00	6.98	7.93	8.86	9.77	10.67	11.54
7	1.84	3.27	4.58	5.82	7.00	8.14	9.26	10.34	11.40	12.44	13.47
8	2.10	3.74	5.24	6.65	8.00	9.31	10.58	11.82	13.03	14.22	15.39
9	2.37	4.21	5.89	7.48	9.00	10.47	11.90	13.29	14.66	16.00	17.32
10	2.63	4.67	6.54	8.31	10.00	11.63	13.22	14.77	16.29	17.78	19.24
11	2.89	5.14	7.20	9.14	11.00	12.80	14.54	16.25	17.92	19.55	21.16
12	3.16	5.61	7.85	9.97	12.00	13.96	15.87	17.73	19.55	21.33	23.09
13	3.42	6.08	8.51	10.80	13.00	15.12	17.19	19.20	21.17	23.11	25.01
14	3.68	6.54	9.16	11.63	14.00	16.29	18.51	20.68	22.80	24.89	26.94
15	3.94	7.01	9.82	12.46	15.00	17.45	19.83	22.16	24.43	26.67	28.86
16	4.21	7.48	10.47	13.29	16.00	18.61	21.15	23.63	26.06	28.44	30.78
17	4.47	7.95	11.13	14.13	17.00	19.78	22.48	25.11	27.69	30.22	32.71
18	4.73	8.41	11.78	14.96	18.00	20.94	23.80	26.59	29.32	32.00	34.63
19	5.00	8.88	12.43	15.78	19.00	22.10	25.12	28.07	30.95	33.78	36.56
20	5.26	9.35	13.09	16.62	20.00	23.27	26.44	29.54	32.58	35.55	38.48
21	5.52	9.82	13.74	17.45	21.00	24.43	27.77	31.02	34.21	37.33	40.40
22	5.78	10.28	14.40	18.28	22.00	25.59	29.09	32.50	35.83	39.11	42.33
23	6.05	10.75	15.05	19.11	23.00	26.76	30.41	33.97	37.46	40.89	44.25
24	6.31	11.22	15.71	19.94	24.00	27.92	31.73	35.45	39.09	42.66	46.18
25	6.57	11.69	16.36	20.77	25.00	29.08	33.05	36.93	40.72	44.44	48.10
26	6.84	12.15	17.02	21.60	26.00	30.25	34.38	38.41	42.35	46.22	50.02
27	7.10	12.62	17.67	22.44	27.00	31.41	35.70	39.88	43.98	48.00	51.95
28	7.36	13.09	18.32	23.27	28.00	32.57	37.02	41.36	45.61	49.78	53.87
29	7.63	13.56	18.98	24.10	29.00	33.74	38.34	42.84	47.24	51.55	55.80
30	7.89	14.02	19.63	24.93	30.00	34.90	39.67	44.31	48.86	53.33	57.72

TABLE 7.6 (CONT.) UNITS PULMONARY TOXICITY DOSE (UPTD) FOR GIVEN PO_2

	PO_2										
Minutes	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
31	8.15	14.49	20.29	25.76	31.00	36.06	40.99	45.78	50.49	55.11	59.64
32	8.41	14.96	20.94	26.59	32.00	37.23	42.31	47.27	52.12	56.89	61.57
33	8.68	15.42	21.60	27.42	33.00	38.39	43.63	48.75	53.75	58.66	63.49
34	8.94	15.89	22.25	28.25	34.00	39.55	44.95	50.22	55.38	60.44	65.42
35	9.20	16.36	22.91	29.08	35.00	40.72	46.28	51.70	57.01	62.22	67.34
36	9.47	16.83	23.56	29.91	36.00	41.88	47.60	53.18	58.64	64.00	69.26
37	9.73	17.29	24.21	30.74	37.00	43.04	48.92	54.65	60.27	65.77	71.19
38	9.99	17.76	24.87	31.58	38.00	44.21	50.24	56.13	61.90	67.55	73.11
39	10.25	18.23	25.52	32.41	39.00	45.37	51.56	57.61	63.52	69.33	75.04
40	10.52	18.70	26.18	33.24	40.00	46.54	52.89	59.09	65.15	71.11	76.96
41	10.78	19.16	26.83	34.07	41.00	47.70	54.21	60.56	66.78	72.89	78.89
42	11.04	19.63	27.49	34.90	42.00	48.86	55.53	62.04	68.41	74.66	80.81
43	11.31	20.10	28.14	35.73	43.00	50.03	56.85	63.52	70.04	76.44	82.73
44	11.57	20.57	28.80	36.56	44.00	51.19	58.18	64.99	71.67	78.22	84.66
45	11.83	21.03	29.45	37.39	45.00	52.35	59.50	66.47	73.30	80.00	86.58
46	12.10	21.50	30.10	38.22	46.00	53.52	60.82	67.95	74.93	81.77	88.51
47	12.36	21.97	30.76	39.05	47.00	54.68	62.14	69.43	76.56	83.55	90.43
48	12.62	22.44	31.41	39.88	48.00	55.84	63.46	70.90	78.18	85.33	92.35
49	12.88	22.90	32.07	40.72	49.00	57.01	64.78	72.38	79.81	87.11	94.28
50	13.15	23.37	32.72	41.55	50.00	58.17	66.11	73.86	81.44	88.88	96.20
51	13.41	23.84	33.38	42.38	51.00	59.33	67.43	75.33	83.07	90.66	98.13
52	13.67	24.31	34.03	43.21	52.00	60.50	68.75	76.81	84.70	92.44	100.05
53	13.94	24.77	34.68	44.04	53.00	61.66	70.07	78.29	86.33	94.22	101.97
54	14.20	25.24	35.34	44.87	54.00	62.82	71.40	79.77	87.96	96.00	103.90
55	14.46	25.71	35.99	45.70	55.00	63.99	72.72	81.24	89.59	97.77	105.82
56	14.72	26.18	36.65	46.53	56.00	65.15	74.04	82.72	91.21	99.55	107.75
57	14.99	26.64	37.30	47.36	57.00	66.31	75.36	84.20	92.84	101.33	109.67
58	15.25	27.11	37.96	48.19	58.00	67.48	76.69	85.67	94.47	103.11	111.59

than a doubling of a diver's resistance

A 1989 study found that a five minute break every 20 minutes allowed for a 12-hour exposure with an average 4% reduction, while divers without breaks reached this 4% in only five hours

With special techniques including the use of helium-based breaks, WKPP exploration divers are able to greatly extend this range

7.5 Oxygen Recovery

While there exists substantial and fairly conclusive information on pulmonary oxygen toxicity, there is no satisfactory research chronicling recovery from CNS toxicity. Bill Hamilton of Hamilton Research has estimated CNS oxygen halftimes at 90 minutes. This data was designed to establish reliable CNS oxygen recovery calculations for multi-level Nitrox computers. The established halftime took into account the oxygen limits for single and daily use, arriving at a decay curve approximation.

Going by this assumption, a diver's CNS clock is reduced by 50 percent for each 90 minutes that pass. Therefore, after three hours a total of 60 percent CNS accumulation will be reduced to 15 percent. The decay hypothetically continues for each 90-minute time period. Understanding how oxygen exposure can reset in this 50 percent reduction process is relevant both to repetitive oxygen diving and for more aggressive technical diving profiles.

Following the dive, convention dictates that a diver's CNS clock is reduced by 50% for each 90 minutes that elapse. Therefore, with reference to the last example, after three hours elapse, the diver's CNS clock will be reduced to 15%. This decay hypothetically continues for each 90-minute time period. Understanding how CNS clock resets in this manner is highly relevant both to repetitive oxygen diving and for more aggressive technical diving profiles. It will be covered more thoroughly later on in this chapter.

The basis of most oxygen limit calculations relates to research done in the mid 1900's in response to wartime requirements of divers on oxygen rebreathers. Unfortunately, today very little new research exists that goes beyond these early studies. Funding limitations and decreased urgency have led interested parties to revisit these older studies and/or resort to mathematical modeling. Because of this, divers who are interested in extending their oxygen exposures are forced to step into an unproven and far riskier area.

Currently, only a few groups such as GUE and the WKPP have systematically applied themselves towards extending the knowledge of practical oxygen use, consistently redefining our understanding of decompression and oxygen exposure. This information, some of which is presented below, is largely the result of these diving activities and no claims are made about whether other divers can safely use it. These findings are undergoing evolution with only a handful of divers as test subjects.

7.5.1 Redefining the Limits of Oxygen Exposure and Oxygen Recovery

Most of the available research on oxygen recovery relates to pulmonary oxygen toxicity. Pulmonary

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6 Lambersten (1955, 1978, 1988); Hall (1967); Clark & Lambersten (1971); Clark (1974); Widell et al. (1974); Hendricks et al. (1977); Harabin et al. (1988).

toxicity is generally considered to be a distinctly different phenomenon from CNS toxicity. As discussed earlier, pulmonary toxicity seems to progress slowly, impacting divers only after very long exposures. Pulmonary toxicity has a fairly clear and measurable progression, one that can be altered by interrupting the oxygen dose with a *break*. These breaks have historically been taken while breathing from an air source and are often called *air breaks*. GUE and the WKPP initiated a system of breaking on helium-based gasses, and have found a marked improvement in oxygen resistance.

Clark & Lambersten summarize pulmonary oxygen recovery as follows[6]:

In contrast to the present lack of truly effective pharmacological measures for extension of oxygen tolerance, a currently useful procedure employs systematic alteration of hyperoxic exposure intervals with relatively brief normoxic intervals to increase markedly the total duration of tolerable exposure to a selected level of hyperoxia within a period of 24 hours or longer. Since this procedure involves the periodic, sequential elevation and reduction of oxygen tension rather than passage of a chemical agent across cellular membrane barriers, it is effective in all organs and tissues affected by oxygen poisoning.

Of particular interest here is the claim that break cycles are effective in all organs and tissues. With respect to pulmonary toxicity, the benefit of break cycles is clearly discussed by Clark & Lambersten. They establish that the "duration of oxygen breathing associated with a 4% reduction in vital capacity is more than doubled by the use of intermittent exposure." However, given that intermittent exposure affects all tissues and organs, it is not unreasonable to assume that breaks would also benefit CNS toxicity. This seems to be borne out empirically. Exploration dives by GUE and the WKPP regularly expose divers to several hundred percent CNS and well beyond the recommended pulmonary exposure. On the longest of these dives, GUE's Jarrod Jablonski and the WKPP's George Irvine are regularly exposed to values of several thousand percent CNS with no symptoms of oxygen toxicity[7].

Three key factors are likely responsible for this success: fitness, regular and strategic break-cycles, and the use of helium-based break gasses. These appear critical in resisting damage from aggressive oxygen exposures. A special section in GUE Resources (www.gue.com/resources) elaborates further on the mechanics of CNS toxicity and how it is possibly tied to stress, fatigue and exhaustion (through the release of catecholines in the body). Fit divers are more likely to tolerate physical demands with reduced levels of stress, as they are less likely to accumulate CO_2.

7 During very long dives (six or more hours at 300 feet), Jablonski and Irvine use regular break-cycles along with strategic break cycles that increase the break time prior to elevated PO_2 (such as at a gas switch). For example, at their 120ft (36m) decompression stop, where their CNS percentage is already well above 300 percent, these divers will utilize a longer "break" of approximately 20 minutes on a reduced oxygen mix. These divers have pioneered the use of helium-based break gasses, instead of the commonly used air mixes, to reduce oxygen content from the 21% in air to a lesser value (usually around 15%). Furthermore, the use of helium reduces breathing resistance and eases lung stress showing all the while great benefits in the reduction of pulmonary irritation.

Chapter 8

Decompression Illness

8.0 Introduction

Historically, decompression theory was considered an advanced topic, one that was beyond the scope of most divers. This led to decompression illness being viewed rather narrowly. Today, there is growing recognition among some that all divers, from novice to technical, will benefit from a more thorough understanding of decompression. A complex phenomenon, decompression illness encourages many to take a closer look at the implications of exposure to elevated ambient pressures. Increased awareness and the desire to understand this complicated phenomenon forces one to look back at the root of this issue and ask, “What is decompression illness anyway?”

8.1 The Mysterious Malady

The turn of the 19th century forever changed the diving world. The development of a pump capable of delivering air under pressure allowed divers the comfort of having a constantly replenished supply of air. This improvement was incorporated into several styles of diving dress, allowing men much greater freedom. The most popular of these was developed by Augustus Siebe and was known as “Siebe’s improved diving dress.” It is the direct ancestor of the modern day deep-sea diving dress.

Unencumbered by the limits imposed by the need for fresh air, divers were now capable of much longer exposures. As a result, diving became much more profitable and, of course, popular. In 1840, a unit of the British Royal Engineers employed these improvements to excavate the remains of a sunken warship. Their divers often spent six to seven hours a day at more than 60 feet. The excavation was successful, yet of all the divers involved, not a single one escaped a rather mysterious malady described as repeated attacks of rheumatism and cold. Today we know this malady as “decompression sickness.”

For more than 150 years, divers, physiologists, biologists, mathematicians, engineers, and lay people have tried to get a grasp on the complicated physiological causes and implications of decompression illness. Today, conventional wisdom tells us that dives within or very near the “no decompression limits” are often considered relatively safe, while dives exceeding these limits are considered more dangerous. In some ways this claim is sound; yet, it seems to imply that individuals within the commonly accepted limits are at a very low risk for decompression illness, and that they need not be concerned about decompression illness. The reality appears to indicate otherwise.

Hyperbaric damage may be represented in many different ways. For example, in the early years, decompression study focused on pain as an indication of DCS. Later studies focused on gas bubbles. These indicated that gas bubbles (thought to be the precursor and eventual cause of painful DCS) were often present in the body even when painful symptoms were not manifest. These asymptomatic bubbles were predicted as early as 1951 by Bateman, Behnke and Doppler, and due to their lack of symptomatic pain, termed “silent.” The advent of ultrasonic monitoring techniques showed that these bubbles were detectable, even though often no symptoms were present[1]. By allowing decompression techniques to be evaluated in a more exact manner than what was possible through symptomatic DCS, they initiated a new age in decompression study.

By measuring bubble formation, Doppler studies proved invaluable in verifying the efficacy of different decompression procedures. They allowed researchers to evaluate these procedures by comparing their results with an upper limit of permissible detectable bubble formation. "Acceptable" profiles would be those that would either prevent any Doppler detectable gas bubble formation or, more commonly, would allow only minor bubbling. The ability of Doppler study to locate bubbles, and the resulting analysis of decompression profiles, led to a discussion of what, if any, would constitute an acceptable level of bubble formation. In other words, the question was, "should decompression tables strive to prevent *any* formation of Doppler detected gas bubbles, or should they strive to maintain an acceptable level of bubbling?"

Generally, during a Doppler study, technicians will measure the amplitude and frequency of bubbles present in a diver's body. Detected bubbles are then ranked on a zero-to-four scale, with zero indicating no detected bubbles and four representing significant bubble formation. Typically, individuals develop symptoms of DCS at around grades three to four. However, some individuals have complained of symptoms even in the absence of detectable bubbles, while others are asymptomatic at grades as high as grade four. What then is a reasonable approach? If bubbles are responsible for DCS, why is this correlation not more obvious?

Realistically, bubble formation during diving is very common. Many experts believe that limited bubble formation may be the standard during hyperbaric exposures. Indeed, the lack of a Doppler-detected bubble may not indicate a completely bubble-free dive. In fact, some research suggests that microbubbles permanently exist in the body, acting as seeds that may be fed by surrounding tissues or blood. Still other studies claim that bubbles form in the arterial side, perhaps in the turbulent blood flow around the nodes of the heart. Such claims are interesting and dynamic attempts to clarify complex interactions in the body. Nonetheless, divers are more interested in practical application than they are in complex theory. What, then, is a responsible way to handle this theoretical debate?

It seems likely that bubble formation has a fairly direct impact on the symptoms of decompression illness, and that especially large collections of bubbles can be very dangerous. It therefore seems prudent to embrace procedures that are likely to limit the formation of excessive bubble formation. These procedures, i.e. slowed ascent rates, limiting multi-ascent dives, and the use of safety stops, are prudent well beyond the scope of theoretical decompression discussions.

All divers should have a reasonably comprehensive understanding of the practical aspects of decompression illness. Such an understanding is essential for all divers, regardless of level, and can serve as a broad foundation for management and prevention. Furthermore, knowledge of hyperbaric injuries can prove essential in the proper management of decompression illness. Frequent diving, especially at more advanced levels, is likely to expose divers to some form of hyperbaric injury. An individual's ability to manage these injuries in him/herself or others is vital to his/her qualifications as a diver and his/her value to the diving team.

8.2 Hyperbaric Illness

1 Spencer & Campbell (1968) were at the forefront of early Doppler work.

Historically, decompression maladies have been distributed across two categories. The first and more common is the result of gas being trapped in the blood and tissues of the body, as a result of changes in ambient pressure. Decompression sickness is the result of gas forming due to changes in ambient pressure. The second malady is the result of gas being introduced into the body's tissues from the over-pressurization of gas-containing structures such as the lungs (e.g. pulmonary barotraumas). Gas introduced into the arterial system in this manner results in arterial gas embolism (AGE) and can have a host of dangerous repercussions.

> Decompression Sickness (DCS) - gas trapped from changes in ambient pressure
>
> Arterial Gas Embolism (AGE)- Gas introduced into the arterial system usually from the rupture of a gas-containing organ, such as the lungs.

As this classification system evolved, it became necessary to be more precise with respect to the nature of the malady and the associated symptoms. From this need emerged a more refined sub-classification system.

8.3 Traditional Classification of Decompression Illness With Sub-Classifications

I. Traditional Classification of Decompression Illness

A. Decompression sickness[2]

- 1. Type I
  - a. Musculoskeletal
  - b. Skin
  - c. Lymphatic
  - d. Fatigue
- 2. Type II
  - a. Neurological
  - b. Cardiorespiratory ('chokes')
  - c. Vestibular/auditory
  - d. Shock

B. Arterial gas embolism

C. Barotrauma

- 1. Locations
  - a. Lung
  - b. Sinus
  - c. Inner ear

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2 The US Air Force classifies sensory symptoms (numbness, paraesthesias) as type I. See Sien & Baumgartner 1990.

d. Middle ear

e. Dental

f. Gastrointestinal

Typically, the assumption has been that decompression sickness is represented by symptoms that arise from the presence of bubbles in the body, and that the size and location of these bubbles are responsible for the different symptoms of decompression sickness. For instance, bubbles trapped in the joints might impinge on nerve endings and cause pain (considered Type I DCS in the above system). Alternatively, bubbles can be trapped in the nervous system and exert pressure on certain parts of the spinal cord causing dysfunction such as paralysis (falling under Type II DCS in the above system). In conformity with this line of thinking, air introduced directly into the arterial system, perhaps during a lung rupture, could carry gas to sensitive regions like the brain, with serious and potentially deadly implications (termed an AGE under the above system).

This traditional system has been widely used, and broadly disseminated as a method for discussing symptoms and determining treatment. However, current uncertainties about the mechanisms responsible for decompression sickness have called into question the accuracy of this system. For example, both AGE and DCS can coexist in a patient, and it is often impossible to clinically differentiate between them. In fact, a review of cases by some 50 experienced hyperbaric doctors demonstrated a disturbing degree of discordance between their individual diagnoses of the same case (Francis & Smith, 1992).

In view of this, some have suggested that one describe the clinical manifestations without attempting to describe the pathophysiology (Francis & Smith, 1992). Under such a system the term *decompression illness* would encompass all manifestations of decompression barotrauma and/or decompression sickness and a range of symptomatic information gathered.

8.4 Reclassification of Decompression Illness

Under the later system, the following information would be gathered:

Clinical manifestations

Time to onset of each manifestation and its pattern of evolution

Tissue inert gas burden (e.g. depth-time profile)

Evidence of barotrauma

I. Reclassification scheme for the description of decompression illness (Francis & Smith, 1991)

A. The presentation of acute decompression illness

1. Evolution

.a. Progressive

b. Static

c. Spontaneously improving

d. Relapsing

B. Manifestation

1. Pain

   a. Limb pain

   b. Girdle pain

2. Cutaneous (skin)
3. Neurological (including audiovestibular)
4. Pulmonary
5. Lymphatic
6. Constitutional (malaise, anorexia, fatigue)
7. Hypotension (low blood pressure)

C. Time of onset

D. Gas burden (e.g. depth-time profile)

E. Evidence of barotrauma (lung, sinus, ear, dental)

Many have adopted the *decompression illness* (as opposed to sickness) nomenclature, but have retained the older Type I and Type II classification system. This has led to confusion among individuals, creating the impression that the differences between the two systems are semantic and that the latter is not an improvement on the former. In fact, the proposed *Francis & Smith system* is more refined and is removed from the burden of errant attempts at pathophysiological assumptions. In other words, the interpretations are focused on symptoms and treatment without attempting to discuss causal mechanisms.

8.5 Barotrauma

Barotraumas are fairly common pressure-related injuries that range from minor injuries, such as mask squeezes, to potentially serious injuries, such as arterial gas embolisms. A barotrauma occurs when the pressure difference between a tissue and an air space region is sufficient to cause tissue damage. A fairly common barotrauma occurs in the middle ear when the middle ear cannot properly equalize with ambient pressure. This “squeeze” may occur either due to congestion, such as with an upper respiratory infection, or due to a congenitally narrowed passage. In other cases, a reverse block may occur when initial congestion is mitigated by medication, only to return after the medication wears off during the dive. This prevents the now-equalized region from releasing excess pressure.

These problems can be particularly challenging if they prevent a diver from descending or ascending, or they result in the rupture of an eardrum. Divers who are injured this way often become very disoriented because, as water moves into the ear canal, it can cause vertigo. Such problems may become even more severe if the diver does not have an astute buddy, or if the team is forced to navigate some distance before surfacing (e.g. in a cave, wreck or under ice). Some divers have been able to limit the consequences of an eardrum rupture by using a finger to prevent cold water from flowing into the ear.

Lung barotrauma can be particularly problematic and gives rise to a variety of conditions with varying severity. During ascents, gas may become trapped in the lungs either through breath holding or regional gas trapping. In such cases, the increased pressure in the lung seeks an outlet, thereby causing tissue damage and escaping into the body. Escaped gas trapped under the skin (*subcutaneous emphysema*) often collects in the neck region. Sometimes this causes a change in voice resonance, while at other times it is obviously present in the tissues. Here, the trapped gas is said to resemble small pebbles, and may or may not encourage a hyperbaric physician to order recompression. Gas trapped in the chest region (*mediastinal emphysema*) may leave the diver with labored breathing. Gasses that escape the lungs but are trapped in the plural lining that surrounds the lungs may also cause breathing distress and could even result in lung collapse[3].

8.6 Arterial Gas Embolism

While gas trapped in the body may result in some of the potentially less severe cases described above, it may also result in conditions that pose an immediate and serious threat. For example, the effects of an arterial gas embolism depend largely on the path and collection site of the trapped gas in the circulatory system. If the gas travels to a delicate area, like the heart, brain, or spinal cord, the outcome can be quite severe. Symptoms of AGE are typically seen almost immediately after surfacing, and include: paralysis, loss of consciousness, convulsions, visual disturbances, dizziness, and difficulty in speaking[4].

8.7 Dissolved Gas DCI

Under the Francis & Smith system, dissolved gas DCI would encompass all dissolved gas phenomena regardless of mechanism or origin of the gas phase. This classification is most closely affiliated with the older Type I and Type II DCS nomenclature; however, the dissolved gas DCI case is then subdivided, based strictly upon represented symptoms, not by any pathophysiological determination.

8.8 Symptoms

Dissolved gas DCI can affect the musculoskeletal system, the lymphatic system, the skin, and organs such as the heart.

8.8.1 Musculoskeletal Symptoms

Pain is the most common manifestation of decompression illness. This pain is usually light or moderate, but can also be extremely severe. Burning, prickling on the skin (*paraesthesia*) or diminished sensitivity, sometimes with partial loss of capacity (*hypaesthesia*), may occur near the affected joint. This pain may

3 Some divers get bogged down in the details of this nomenclature system. While any diver should be acquainted with some of diving's more common maladies, it is most important for them to understand the general symptoms of diving related maladies so, when appropriate, that they may be encouraged to seek professional treatment.

4 Gas may enter the arterial system due to a barotrauma or through a PFO

occasionally be relieved by a slight increase in pressure like standing or by using a pressure cuff (Rudge and Stone, 1991). Generally, in cases like these, there are no accompanying signs of joint inflammation such as tenderness, swelling, effusion, or limitation of movement (Bennett and Elliott, 1998). Most commonly, pain is reported in the upper limbs; however, longer exposures or working dives seem to elicit knee pain. This is in keeping with other findings. In bounce divers, pain is common in upper limbs (Rivera, 1964; Stark, 1964; Elliott et al., 1974), while in caisson workers and saturation divers, pain is more likely to occur in the lower extremities (Keays, 1909; Erdman, 1912; Golding et al., 1960; Lam & Yau, 1988).

Certainly the presence of joint pain makes DCI noticeable to the victim, and increases the likelihood of it being reported to a physician. The fact that joint pain is common calls attention to the fact that joints are a troublesome area. Joints are problematic sites for a number of reasons. First, while their dynamic action likely attracts increased blood flow with a rich inert gas supply, their angular nature creates sections of impeded blood flow. Also, joints tend to be abused in daily life and may harbor scar tissue, further impeding circulatory efficiency.

The severity of localized joint pain can vary significantly. In some cases, this pain can be a very mild or even transient ache, coined “niggles” by commercial divers. However, it can also be very severe, and was described by one victim as similar to “knives twisting in the joints.” Most commonly, joint DCI lies probably somewhere in between these two extremes, and is generally an easily survivable, although unpleasant, experience.

8.8.2 Skin Symptoms

Cutaneous symptoms, or *skin bends*, may be as slight as mild itching, or as pronounced as a conspicuous skin rash. Rashes can be somewhat common in individuals with disrupted surficial circulation (e.g., those with scar tissue). Some divers with scar tissue from previous accidents commonly get skin symptoms. Skin bends may be an indication that the diver is close to a particular limit, or that there may be an interruption in cutaneous circulation. In addition to scare tissue, skin symptoms may be the result of some related circulatory inefficiency, or the result of heated skin (such as occurs in a hot shower, bringing blood and its inert gas load rapidly to the warmed surface of the skin).

Generally, people consider symptoms like skin bends less noteworthy than severe joint pain. Yet the concept of “toughing it out,” often associated with lesser symptoms, may have notable long-term repercussions that should encourage individuals to seek the advice of an expert. In many cases, treatment of skin bends is not considered necessary; yet, some forms of skin bends can precede life-threatening decompression illness (Keays, 1909; Thorne, 1941; Davis, 1990). While such severity may be the exception, divers should be aware that some forms of DCI could upgrade from an apparently mild situation into a serious life-threatening one.

8.8.3. Isobaric Counterdiffusion

Isobaric counterdiffusion was first described in a report on skin symptoms (Blenkarn et al., 1971). It was identified in commercial diving applications where divers were held in a decompression bell, usually while breathing a gas different than ambient. In this context, isobaric counterdiffusion is thought to occur when the surrounding gas is more diffusible than the diver’s breathing gas, e.g. when breathing Nitrox in a helium-oxygen environment. Later, this malady was discovered in divers who were not associated with diving bells. It seems that isobaric counterdiffusion is most common when divers are switching breathing gasses, thereby analogically reproducing the conditions existing in the case of the original decompression bell by creating a notable pressure gradient. Opinion varies about the risk of this phenomenon, however, with thousands of mixed-gas dives accomplished and only a small handful of ambiguous reports available, the liklihood that divers will ever see such a situation seems far removed.

8.8.4 Lymphatic System

Occasionally, divers may experience some soft tissue swelling that may be accompanied by pain. While the pain may be slight, the swelling can be significant. Some claim that such localized swelling is due to bubbles obstructing the lymphatic vessels (Heaney, 1988; Daugherty, 1988; Ideka et al., 1988; Hamilton, 1991). The swelling commonly involves the breast, abdomen, face or extremities. In some cases, physicians may opt not to treat even respectable swelling with recompression. Recompression may relieve associated pain, but typically a reduction in swelling may take several days.

8.8.5 Heart

Inert gas washout is very effectively performed in the heart due its efficient blood flow and high capillary density. Significant bubble formation in the heart is, therefore, expected to be quite low, and the risk limited. However, one case of atrioventricular block has been documented, occurring simultaneously with musculoskeletal decompression illness (Halpern & Greenstein, 1981). The case involved a 33-year-old diver who, following recompression, returned to normal 36 hours after the dive.

Some researchers have claimed that the initial creation of bubbles may occur in the heart. If this were the case, tiny microbubbles might have to survive long enough to come into contact with inert gas-rich tissue beds and generate larger stable bubbles. Such theories of bubble initiation could help explain certain aspects of decompression illness, but also have unsettling possibilities, namely, that it may be common for minor bubble formation to occur in the arterial system. If this were the case, then the liklihood of formation and/or proliferation of bubbles must necesarily be low due to the small fraction of DCI risk.

8.8.6 General Fatigue

Fatigue-triggered DCI is an especially problematic symptom, since divers are frequently exerting themselves, often with less than normal sleep, on the day of a dive. For this reason, DCI fatigue may be underreported in some situations, or mistaken for general fatigue in others. This fact serves to cast a shadow over the available DCI data, given that most divers are less likely to report a case of fatigue than an unusual case of joint pain. Even so, fatigue is usually reported alongside the more definitive symptoms of decompression illness. For example, extreme fatigue was reported to DAN (Divers Alert Network) as an initial symptom in 5.7% of divers with DCI, while 17.1% of these divers reported extreme fatigue as one of multiple symptoms. To increase safety and to reduce the risk of masked symptoms, divers should strive to be rested and remain well-hydrated during all diving activities.

8.8.7 Venous Gas Bubbles

Following hyperbaric exposure, it is not at all uncommon for reasonable levels of inert gas to be found in the venous system. Doppler studies typically look for bubbles in the venous side of the circulatory system, where one would expect a much greater likelihood of bubble formation. Inert gas coming out of solution in the tissues will be deposited in the venous system, as might bubbles that may have formed in the tissues. The potential for bubble accumulation in the venous side is notable. Doppler-detectable bubbling is not at all uncommon, even on relatively minor exposures. Often, the bubbles found in the venous side are minor, and can be easily rectified by the pulmonary filtering capacity of the lungs.

Bubbles that exist or form in the arterial side may cause immediate problems if transported to sensitive regions such as the brain or spinal cord. Alternatively, they will travel to tissues and end up migrating into the venous system. Air in the venous blood can cause damage to the pulmonary vascular endothelium and can result in pulmonary edema (Ence & Gong, 1979). When the vascular bubble count becomes elevated, symptoms may become quite evident with dyspnoea or coughing. Under these conditions, the normally efficient filtering of the lungs is impaired, possibly allowing bubbles to travel to the arterial system and to give rise to neurological symptoms. Such a transfer of venous bubbles to the arterial system is also possible in individuals with a patent foramen ovale (PFO).

It is possible for the venous bubble count to become high enough to create a critical concern for the victim's life. In some cases, the lungs may become overwhelmed with excess vascular bubbling, making it very difficult for the diver to properly ventilate. Such a venous gas load may be the result of several factors. It can result from multi-level diving, where a diver, after spending time at depth, follows his/her ascent to or near the surface with a return to depth. Each of these ascents and returns to depth forces dissolved gas out of solution and often result in bubbling. These bubbles may be of limited concern, but upon a diver's return to depth the bubbles will recompress, and later, upon ascent, reexpand. Subsequent ascents and descents may also multiply the bubbles. When the diver finally returns to the surface to stay, the accumulated inert gas may overwhelm the lungs and results in a critical ventilation problem. It seems likely that this situation may also occur in cases where divers have an accumulation of inert gas from previous dives. Fatty tissues of the body act as an excellent inert gas reservoir and may predispose individuals to these problems.

8.9 Contributing Factors to Decompression Illness

In many ways, DCI is a statistical event, one that leads some to describe its development in strictly statistical terms. Using analytical tools like *maximum likelihood*, these researchers try to fix a risk to given profiles. Their attempts rely largely on previous diving exposures, and thus are highly limited in their predictive potential. Statistical analysis is an interesting tool, but it often abandons interpretive efforts and ignores certain very successful advances in decompression theory.

While the phenomenon of decompression illness remains somewhat mysterious, certain contributing factors seem to increase individual risk. While the degree to which individual factors impact a given DCI event is debatable, most informed divers agree that several factors impact an individual's susceptibility. The following treatment of predisposing factors is meant as a general guide, and is the result of both scientific inquiry and practical diving experience.

8.9.1 Inexperience/Ignorance

It is important to emphasize the crucial role a diver's understanding plays in his/her own safety and well-

5 Elliot, D. & Bennett, P. (1993) Underwater Accidents. In *The Physiology and Medicine of Diving,* 4th edn, p. 240. Ed. P. Bennett, & D. Elliott. London: W. B. Saunders Co. Ltd.

being as well as that of the team. A review of 114 SCUBA-related deaths in 1989 indicated that 60% of these deaths involved divers who had undertaken only 20 dives or less[5]. Uninformed or inexperienced divers with poor skills are, indeed, accidents waiting to happen. Unfortunately, the future does not seem brighter, as the dive industry moves to shorter courses with less of a time commitment and less information. Often, even individuals with reasonable diving experience have only a limited grasp of the essentials. In one reported case, an experienced Trimix diver had a problem with a decompression bottle; rather than breathe the Trimix on his back while fixing the problem he did an emergency ascent from 100 feet on a breath hold. The misinformed belief that breathing mix at moderate depth is dangerous precipitated a near-fatality in an otherwise benign situation.

8.9.2 Age

Early evidence regarding the possible role age plays in DCI comes from an assessment of the fact that an 18 year old was twice as susceptible to DCI as a 28 year old (Gray, 1951). Age has been implicated as a contributing factor in DCI in at least 11 reports on diving, altitude, and caisson work (Gray, 1951, Bradley, 1987), while only three reports claim no contributory relationship (Wise, 1963; Dembertet al., 1984; Lam & Yau, 1989).

To be sure, there is no irrefutable evidence that, by itself, age is a contributing factor in DCI. It is more likely that factors associated with aging are what play a more significant role in individual DCI onset. As males age, they often gain weight at approximately more than one pound per year, after the age of 30. This increase in fat lends itself to inefficient offgassing and DCI vulnerability. Furthermore, aging initiates other potentially contributory causes, such as degenerative joint disease, changes in pulmonary function and cardiovascular disease (Dembert, 1989). Despite these potential issues, however, it is likely that many of the risks associated with increasing age can be offset by a responsible lifestyle that includes exercise and a healthy diet.

8.9.3 Linear Density

At least 15 studies have found a correlation between fat content and DCI risk (Dembert, 1989; Lam & Yau, 1989), while only two found none (Wise, 1963; Curley et al., 1989). What these studies suggest is that fat's high nitrogen solubility increases absorption and bubble growth. Fat, for example, absorbs about six times as much nitrogen as an equal weight of blood (Vernon, 1967), and is problematic as a reservoir for bubble growth. In their early studies, Boycott & Damant asserted that "...obesity doubtless favors death after long exposures because fat acts as a reservoir..."(Boycott & Damant, 1908).

Fatty tissue's readiness to absorb and store inert gas (most particularly nitrogen) can greatly delay the elimination phase, and can create numerous decompression-related problems. For example, inert gas elimination from fatty subjects can be slowed by as much 40% as compared to lean subjects, potentially resulting in widely divergent acceptable decompression constraints (Shaw et al., 1935). An example of such variations in DCI risk can be found in Gray's 1951 research. Furthermore, altitude decompression studies of 49,000 subjects that measure both height and weight estimated that a 178 cm (70 inches) man weighing 89 kg (196 lb) was twice as susceptible to DCI as a 57.3 kg (126 lb) man of the same height (Gray, 1951).

Other studies indicate that this susceptibility may be even greater. For example, it has been determined that the fattest 25% of the diving population, as measured by skin fold thickness, have a ten-fold increase in DCI incidence. In conclusion, then, the vast majority of evidence indicates that overweight divers are at a much greater risk of DCI, making it only reasonable that they should seek to reduce their fat content and to increase their fitness level.

8.9.4 Smoking

The wide range of negative impacts on individual health and vitality should be encouragement enough to avoid smoking, yet nicotine addiction remains. With approximately 500 chemicals and a host of negative symptoms present, giving up smoking could be the best choice any individual could make. This should be obvious from the fact that approximately 420,000 people die each year in smoking-related deaths, and 300,000 cases of second-hand smoke-related illnesses are reported.

With respect to a number of factors, smokers increase their risk of ascent-related pulmonary barotrauma such as AGE. First, nicotine increases blood pressure, one's heart rate and coronary vasoconstriction. Second, smoking introduces tar and nicotine, which cause increased bronchospasm, depressed cilial activity, and increased mucus production. These factors may lead to intrapulmonary air trapping and increased pulmonary infection.

Carboxyhaemoglonin levels in smokers range from 5% to 9%, with significant psychomotor effects being reported from exposure to this level of carbon monoxide (Diving and Subaquatic Medicine, 1992). Furthermore, with smoking, one's general fitness capacity declines. Increased heart rate, and decreased stroke volume (the opposite effect of aerobic training), is commonplace. Reduced blood volume also results from prolonged smoking, which undermines the hydration attempts of responsible divers. Lastly, increased congestion from smoking is also likely to predispose individuals to sinus and middle ear barotrauma.

Approximately 15% of a smoker's hemoglobin is bound to carbon monoxide, thereby reducing circulatory efficiency. When called upon to transport required oxygen to tissues and to remove carbon dioxide, bound hemoglobin are helpless to assist, reducing oxygenation and increasing CO_2 levels. In addition to its potential for increasing DCI risk, smoking place the diver in serious peril by limiting oxygen intake precisely when it is needed most. Furthermore, there are many indications that CO_2 plays a prominent role in a host of physiological problems, and is likely a key component in episodes of oxygen toxicity. In general, there are likely few things that rank as highly for general physical degradation as does smoking.

8.9.5 Fitness

Of the many contributory factors associated with DCI, fitness often sparks the greatest debate. Some individuals in the diving community scorn the concept that fitness has relevance to diving safety and DCI resistance. In the same way that some organizations have debated the need for swimming ability in diving activity, so have others debated the need for fitness. In much the same way that competence in the water encourages individual comfort, fitness promotes proficiency and ability in a wide array of situations. While the specific impact of fitness on DCI is complicated, fitness and aerobic capacity clearly deserve more attention than they have received in the selection, training, and maintenance of divers (Thompson et al., 1984).

Divers with a high VO_2 max and anaerobic threshold are normally able to work harder and with greater endurance than their less-fit companions (Bennett & Elliott, 1998). This aerobic fitness impacts circulatory efficiency and decompression effectiveness. Highly fit individuals have been able to filter grade 4 bubbles in the pulmonary system, returning to a 0-bubble grade in less than an hour. Such near-freakish occurrences are clear evidence that the role of fitness deserves more respect and a much closer review. While individual variation is a dominant feature of DCI risk, it seems likely that at least some of the individual factors impacting DCI are directly controllable. For example, researchers have discovered wide individual variation, but are able to effectively predict group susceptibility by correlating them with variables such as age, body fat content, and physical condition (Gray, 1951).

8.9.6 Exercise

In the context of diving, exercise can create contradictory results; but in most cases, these results will provide us with insight into safer diving practices. For example, researchers discovered that exercise performed at depth seems to increase on-gassing through elevated blood flow to muscles, and may require as much as three times the decompression time of dry, rested divers. Decompression illness occures most frequently in limbs exercised at depth[6].

Heavy exercise during or after decompression seems to increase the likelihood of bubble formation, possibly from cavitation or perhaps from shearing forces like viscous adhesion. In the first half of the twentieth century, U.S. and Royal Navy divers routinely exercised during decompression because it was thought to increase inert gas elimination. However, Van Der Aue et al. (1949) discovered a 34% increase in DCI incidence for divers that exercised for two hours after no-stop dives. Despite the fact that these tests only included work after dives, Van Der Aue's recommendation that all forms of exercise be avoided became the recognized standard.

Light exercise during decompression seems likely to increase blood flow, possibly increasing off-gassing efficiency. Evidence for this assertion was discovered in altitude decompression trials where subjects either rested or exercised during oxygen breathing prior to decompression to 30,000ft (9144m). During this testing, 10 of 16 resting trials resulted in DCI, while zero of 10 exercising trials resulted in DCI. Further indication that light exercise may be beneficial came in the early 1980s, as divers performing light exercise for 60 minutes at depth showed a roughly 30% decrease in decompression time. The crucial delineation here is almost certainly found in light non-fatiguing exercise that will not stress the body and/or joints.[7]

8.9.7 Dehydration

Some experts estimate that most individuals go through life in a constant state of dehydration. An individual should drink at least one gallon of water each day, yet very few people manage even half that much. All too often an individual will consume few nourishing liquids, instead choosing to drink diuretics like coffee in the morning, compounded further with caffinated soft drinks and often alcohol later in the day. Such drinks provide limited benefit for hydration, as the caffeine content acts to dehydrate the body. To reverse this trend, one's diet should be filled with fruits, juices, and water throughout the day. Divers, especially, should take care to avoid dehydration as they are often active in the hot sun and may need an even greater quantity of water to remain hydrated. It is common for

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6 Vann, r. & Thalmann, e. (1993) Oxygen Toxicity. In *The Physiology and Medicine of Diving,* 4th edn, p. 382 . Ed. P. Bennett, & D. Elliott. London: W. B. Saunders Co. Ltd.
7 Vann, r. & Thalmann, e. (1993) Oxygen Toxicity. In *The Physiology and Medicine of Diving,* 4th edn, p. 382 . Ed. P. Bennett, & D. Elliott. London: W. B. Saunders Co. Ltd.

athletes to drink two or more gallons of water a day to maintain health and vitality. Clearly, to maximize hydration, the use of diuretics like caffeine and alcohol should be avoided.

Jaminet (1871) reported that in caisson workers with DCI symptoms, the specific gravity of their urine was higher. This suggests that dehydration may be a precipitating factor in DCI, or possibly an associated symptom. Many leading divers are convinced that dehydration exacerbates the risk and severity of DCI. Attempts to measure plasma volume and haematocrit values in individuals with severe decompression illness found that normal blood values were both notably reduced. Plasma volume was found to be 50% less than normal, and haematocrit values 32% less (Bruner et al, 1964)[8]. As dehydration and hypovolemia greatly impact not only the microcirculation in the skin and muscular system, but also the joints and bone, this decrease in circulation can encourage microbubble release and encourage DCI. Dehydration may also lead to severe DCI in situations that might otherwise remain mild.

Some divers consume large amounts of isotonic drinks such as Gatorade or Powerade prior to, during, and following diving activity. Consumption of such sodium-rich drinks should be done sparingly, as the excess sodium may actually promote dehydration. Water is always an excellent option and is free from the sodium-related problems associated with isotonic drinks. Individuals that sweat a great deal or desire some carbohydrate replenishment may use isotonics sparingly, but the emphasis should be on hydration with water. For those interested in both carbohydrate fuel and good levels of hydration, fruits are excellent sources of additional water (often composed of up to 80% water) and carbohydrates.

8.9.8 Temperature

Colder tissue will hold more gas in solution, while cold water immersion reduces peripheral blood flow, thereby reducing off-gassing efficiency[9]. However, depending on exertion levels, cold during on-gassing at depth may reduce perfusion and total absorption. Mild hypothermia, therefore, is likely to reduce perfusion **and** the body's ability to remove inert gas. In general, exerting at depth and returning to a cold decompression are a bad combination.

8.9.9 Physical Injury

Injuries such as a sprained joint or a previous incidence of DCI are thought to increase future risk of DCI through scarring and alteration in local perfusion. In fact, scar tissue from even limited injuries might possibly alter blood flow, allowing for a reduction in local perfusion. Some Doppler technicians indicate that injuries often create a noticeable difference in bubble frequency, even in areas of very old injuries such as youthful broken bones. It is possible that operations, particularly more invasive ones, and even more minor injuries, such as those incurred from fatigue caused by long distance running, may create local perfusion reductions. In some cases, even minor surface contusions may produce increased bubble potential.

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8 Buhlmann, 1995

9 Some studies have indicated muscle perfusion rates can be halved, potentially doubling the required duration of decompression

8.9.10 Diving Profiles

Deeper dives, with more decompression, display an increased risk of DCI. This is likely the result of increased gas loading to the tissues, especially those with slower rates of release. While studying saturation divers, Behnke (1947) suggested that approximatlely 75% of the total body nitrogen is eliminated from lean tissues in about two hours, but that the small amount left in fatty tissues and low perfusion regions took many hours to be eliminated. Consequently, deeper dives load tissues with a greater volume of inert gas, reducing the time of release and increasing the amount of inert gas found in the slower tissues. Furthermore, diving profiles for deep dives do not have nearly the degree of supplementary test data that can support a decompression schedule.

Rapid ascents, such as are common in the novice open water community, are a direct violation of decompression requirements. Individuals often seem to forget that decompression profiles incorporate a slow ascent rate (usually about 30ft/min), and a violation of this rate is similar to staying beyond a no decompression limit or choosing to ignore a forced decompression stop.

Multiple ascents can allow the formation of gas emboli that can be trapped in the pulmonary filter and then recompressed on subsequent descents. The final ascent could then allow a now greater number of gas emboli to reach the pulmonary filter; thereby perhaps reducing gas transfer or overloading the lungs and preventing adequate respiration. A fringe dive that is likely to produce DCI has an increased likelihood of neurological DCI if one surfaces during the profile.

Repetitive dives allow for residual nitrogen and therefore tend to increase the risk of DCI. Difficulty in predicting how effectively this gas will leave the tissues during a surface interval and assessing the impact of additional inert gas at the onset of a dive further complicates the decompression picture. The production of asymptotic bubbles, such as those detected by Doppler, may be especially likely to precipitate DCI in later diving episodes.

Altitude diving requires special tables due to reduced surface pressure. Also, traveling to altitude after a dive may provoke DCI by producing or expanding existing bubbles. Airplane travel may be problematic due to reduced cabin pressure, especially if a cabin pressurization failure were to occur. Additional problems associated with air travel include dehydration, which may predispose individuals to later DCI risk.

Horizontal position during decompression or safety stops results in an increased rate of gas elimination when compared to vertical divers whose bloodflows to the lungs are more uniform. In order to maximize decompression efficiency divers should maintain a horizontal position during the off-gassing phase.

8.9.11 Reverse Profile

Reverse profiles are profiles that have a diver doing a shallow dive first and then following that with a deeper dive. Historically, these profiles have been strongly discouraged by training organizations. What is remarkable about reverse profiles is that nobody seems to have a clear answer as to why they are discouraged, and who first prescribed against them. Apparently, the rule against reverse profiles was tied to bottom time efficiency and, over time, got distorted into a myth about diving safety.

Current research seems to make it fairly clear that there are no particularly obvious problems associated with reverse dive profiles in recreational, commercial, military or scientific diving. It is also clear that, on a regular basis, divers seem to be doing reverse profiles without incident. When occasional incidences of

DCS did occur with reverse profiles, it was at a statistically lower rate than for forward profiles. What this means is that, in the field, decompression algorithms and dive computers are adequately handling the question of reverse dive profiles.

There seems to be no basis in diving experience to draw the conclusion that reverse profiles are inherently more dangerous than forward profiles. However, among decompression modelers there are strong reservations against completely retracting the warnings against doing reverse dive profiles. This is because bubble models show that divers can really get into trouble on an improperly planned/executed reverse dive profile. There is general concern that divers, especially inexperienced ones, would get the wrong message about reverse profiles and think that it was okay to do them without any special considerations. Nonetheless, one can argue that, given the lack of data here, the prohibition of reverse profiles is simply arbitrary.

8.10 PFO

Patent foramen ovale (PFO) is not a true cardiac malformation, but a remnant characteristic of the fetal heart. The foramen ovale is an oval-shaped opening, covered by a tissue flap. This opening permits the passage of blood from the right atrium to the left atrium and to the general arterial system, while reverse flow is prevented when backpressure closes the flap. After birth, this flap valve usually adheres permanently to the atrial septal wall and the passage of blood from the right atrium to the left is terminated.

In about 30% of the normal and healthy population, full closure of the foramen ovale does not take place. In cases where the foramen ovale is not permanently closed, the pressure difference between the right and left atria usually pushes the flap valve against the borders of the foramen. However, certain situations alter the pressure difference and allow backflow; these include clearing one's ears, coughing, or vomiting.

increases in intrathoracic pressure may cause the opening of the foramen ovale. In the presence of a patent foramen ovale, bubbles that are likely present in venous blood may pass directly into the arterial circulation and cause injuries typical of decompression illness and arterial gas embolism. Such cases, where gas is passed via the foramen ovale, may trigger severe DCI or embolism cases in modest or even very conservative diving profiles. While debate exists as to the severity of PFO risk, it seems very likely that divers with PFO's are at an elevated risk for severe DCI. While the risk of bubble formation likely remains the same for divers with and without a PFO, this condition seems very likely to increase the risk of serious DCI and/or death. Responsible divers should be tested for the presence of a PFO.

8.11 Complement Activation and DCI

The *complement system* consists of circulating proteins that, when activated, participate in blood clotting, white cell aggregation, and the release of histamine and other inflammatory mediators. Some researchers have postulated that bubble formation in the body results in complement activation and DCI formation and/or aggravation. It may be that some or even all the symptoms of DCI are immune responses to bubbles in the body. Immune response symptoms, which include fatigue and joint pain, might easily be confused with, or even described as, DCI. More likely, compliment activation plays a sporadic and participatory role (if at all) in the complicated symptoms known by the term DCI.

Chapter 9

Decompression Mechanics

9.0 Background

Present data seem to indicate that recreational SCUBA diving, although performed within the no-decompression limits and following ascent criteria calculated, may induce the development of visible gas bubbles in the majority of divers, which persist for more than two hours after the end of the dive. The presence of these "silent" bubbles is actually associated with cardiac changes, suggesting a significant right ventricular overload, and a possible impairment of ventricular relaxation. Humoral changes consistent with a biologically relevant effect of circulating bubbles, both in terms of damaging potential for pulmonary endothelium and of activation of reactive systems, have also been observed[1].

9.1 Introduction

For many people, decompression sickness and its prevention are the most mysterious aspects of technical diving. As divers progress into more robust diving schedules they often find themselves wondering about the "magic" of proper decompression profiles. Current available information makes decompression seem less dangerous. However, individuals must always keep in mind that anytime they dive, particularly outside the common recreational limits, they have become test subjects. Even common "technical" diving profiles have relatively little data to support their veracity. Decompression logistics are intriguing, with many individuals striving to bring as much refinement to the process as possible. However, divers must realize that decompression is a highly variable process, leaving even the industry's leading "experts" with unanswered questions. Bill Hamilton, a popular decompression modeler, even went so far as to say that decompression tables should be written in disappearing ink.

Sometimes, on the very same dive, different divers will follow vastly different decompression profiles, with very liberal divers experiencing the same degree of success as divers who were more conservative. There even exists a small number of divers who are simply not able to dive aggressive (i.e. deep and/or long) profiles without suffering some form of DCI, regardless of the decompression schedule they follow. While many aspects of DCI are mysterious, there seems to be a common thread linking together highly susceptible divers. Many of these divers suffer from poor fitness, high body fat content, and dehydration. Ironically, some of these issues, e.g. risk of DCS due to obesity, were recognized early on by decompression theorists like Haldane, but not focused on by later researchers. Nonetheless, most sensible divers have tried to establish a good balance between the technical side of decompression and an awareness of fitness and other contributors to efficient decompression. Regardless of its impact on diving, everyone should strive to maintain a reasonable level of fitness if for no other reason than for general health; obesity and poor fitness have negatively impact general health and well-being. Leaving health aside, the feeling found in being fit is its own reward. On the question of decompression

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1 Marabotti, C., Chiesa, F., Scalzini, A., Antonelli, F., Lari, R., Franchini, C., & Data, P. G. (1999) Cardiac and humoral changes induced by recreational scuba diving. In *Undersea Hyper Med.* **26** (3), 151-158.

efficiency, there is limited research that precisely defines the benefits of fitness. However, reflection on key elements at work in decompression, like fat content, circulation, and respiratory efficiency, point one in a direction of responsible fitness.

9.2 Deep Stops

Along with other divers, WKPP and GUE divers have been experimenting with the various stages of the decompression profile for more than a decade. *Deep stops* refer to the practice of starting staged decompressions deeper than conventional dissolved gas models recommend. In some cases, these differences can be as much as 50 or more feet. While a great deal has been written about deep stop philosophy, most of these early stops were intuitively calculated. To be sure, some of the research done by Brian Hills and others did assert the value of deep stops. However, these early studies were not well known, and the actual procedure not easily replicated by the technical diver. Indeed, most of these early efforts were quite literally decompression "by feel", as the benefits of deep stops seemed slow to unfold.

Several years of actively implementing deep stops established that what was a good intuitive system was also an effective one. However, to enable other divers to replicate this profile and to encourage further research, one needed a more refined approach. This led to decompression table experimentation with Erik Baker, and to working within the parameters of a gradient system (basically, the idea that stops are curtailed by a chosen percentage of the compartment limit). Here, the two main issues with respect to deep stops are the fixing of a *deepest possible stop depth* (entering decompression, i.e. the depth at which one's compartment pressure exceeds ambient pressure), and the *gradient factor* (or the degree to which the leading compartment's theoretical maximum pressure is "pushed") [2].

9.3 Deep Stop Details

There is a lot of confusion in the technical diving community surrounding deep stops. This is because dissolved gas (Haldanian) models, like the Buhlmann Algorithm, do not or cannot address this issue. The problem has been that most programs have used the ascent-limiting criteria of M-values at face-value without considering other parameters, such as the rate of change in gradients, and the depth at which leading compartment gas-loading equals ambient pressure.

One of the main tenets of the dissolved gas model is that M-values are empirically verified. This means that if X number of divers do the schedule with no or low incidence of DCI, then the M-values are "acceptable." However, much of the data here is centered on compartment loading and M-values during decompression stops and surfacing. There are no big changes in ambient pressure, or M-value gradients, as divers go from one stop to the next in 10fsw increments. However, there are often large gradients involved as the diver ascends from depth to the first stop. In particular, there is a point during the ascent when the compartment with the greatest gas-loading will equal the ambient pressure. At that point the M-value gradient equals zero and represents the beginning of the decompression zone.

Calculated on M-values alone, the first stop is usually much shallower than the depth where the leading compartment gas-loading equals ambient pressure; usually in the order of 50fsw or 60fsw or more. That means that as the diver ascends to the first stop, s/he passes the bottom of the decompression zone (M-value gradient = 0), and goes clear across it to the top of the zone (M-value gradient = maximum). The diver will never again experience such a rapid change in the M-value gradient. The essence of the

2 This material is integrated into the GUE's decompression software, and elucidated in the help files.

dissolved-gas model is to, in effect, control the rate of change in compartment gradients through the use of M-values.

For example, consider a 17/33 Trimix dive to 250fsw for 20 minutes. The decompression model uses Buhlmann ZH-L16B coefficients; the fastest compartment is No. 1b with a 1.88 minute half time for helium, and a 5.0 minute half time for nitrogen. Running a straight calculation with no conservatism factors, according to this model, the first decompression stop will be at 80fsw. However, the compartment with the greatest gas-loading (in this case, the fastest compartment) had a compartment pressure equal to ambient pressure at 186fsw. This means that, technically, the "decompression zone" started at 186fsw (M-value gradient = 0), whereas the model established the first calculated decompression stop as shallow as 80 feet.

This means that the ascent to the first stop allows a change in M-value gradient which is five times faster than that allowed during the rest of the decompression. This is a likely reason why many divers have reported that they have benefited from deep stops, because deep stops serve to reduce the rate of change in gradients. On the other hand, deep stops cannot be made too deep (in this case, no deeper than 180fsw), or they will be doing nothing but uploading more gas in the fastest compartment. The maximum possible stop is also often very similar to a stop that is roughly 2ATA shallower than the maximum depth. This ad hoc rule is often very similar to a calculated max stop.

9.4 Deep Stop Advantages

By allowing for more optimal off-gassing during decompression, deep stops may have several advantages. To understand one of these advantages, it is necessary to understand the important differences that exist between the gas phase of gas elimination and the dissolved phase of gas elimination. Most traditional decompression modeling assumes that gas remains in solution, and the best method for eliminating it is to reduce the ambient pressure to a minimum that falls short of producing bubbles. Today we know that that the belief that all gas remains in solution during decompression is unjustified; bubbles are almost universally present. Thus, during bubble formation, some inert gas must be eliminated through the gas phase. Brian Hills was the first to strongly advocate this idea, and to argue that the dynamics of gas phase elimination should be considered in decompression modeling. This is because the dynamics of gas elimination from the gas phase are markedly different from those of the dissolved gas phase. To simplify, the driving gradient for dissolved gas elimination is increased with reduced depth, while the gradient for gas removal from bubbles is increased with increased depth. This may seem counter-intuitive, but the difference is that gas in the gas phase (bubbles) must exist at ambient pressure, and gas in solution (dissolved) can be either greater than (supersaturated) or less than (undersaturated) ambient pressure.

To illustrate, imagine a bubble forming during an ascent to the surface from an air dive. Any gas in the gas phase will expand until the pressure in the bubble is approximately equal to ambient pressure. The pressure in the bubble will always be slightly greater due to the effects of surface tension of the bubble and the confining effects of surrounding tissue. Gasses will diffuse from tissue into the bubble, so that the bubble's gas composition will reflect that of the tissue. Based on experimental measurements, gas in bubble form is composed of saturated water vapor (47 mmHg) and elevated partial pressure of oxygen and carbon dioxide in the tissues; which can be approximated by use of venous blood values. Inert gas, nitrogen in this case, will diffuse into the bubble to occupy the remainder of the pressure, up to ambient pressure minus surface tension and the effects of tissue confinement. Based on experimental measurements, Hills approximated the surface tension and effects of tissue confinement as 133 mmHg (1ATA = 760 mmHg = 33fsw). The driving gradient to remove nitrogen from the bubble is the difference in nitrogen partial pressure inside the bubble versus nitrogen outside the bubble. The partial pressure of nitrogen inside of the bubble is always slightly greater than outside, due to the effect of surface tension and tissue compression, as well as the difference between arterial and tissue oxygen partial pressure. The difference in oxygen partial pressure between arterial blood and tissue is the oxygen window. Because the bubble exists at ambient pressure, and because the partial pressure of oxygen in the bubble is less than arterial blood, nitrogen will diffuse into the bubble to occupy the vacancy due to the lower partial pressure of oxygen. Thus, the oxygen window is an important force for removing gas from bubbles.

Without elaborating on equation derivation (c.f. Hills, Van Liew or Wienke), the following discussion uses the equations that Hills derived to illustrate the effect of increased depth on a bubble. Based on both theory and experimental work, Hills derived the relation for the nitrogen gradient inside to outside of a bubble as:

$$\Delta PN_2 = P(1\text{-}x) + 47x - 133 \text{ mmHg}$$

Where **P** represents ambient pressure and **x** represents the fraction of nitrogen in the gas mixture. If a bubble occurred while breathing air at 4 ATA, the gradient for nitrogen removal would be:

$$\Delta PN_2 = 3040 \text{ mmHg } (1\text{-}0.78) + 47 \text{ mmHg}(0.78) - 133 \text{ mmHg} = 542 \text{ mmHg}$$

Thus, the gradient for nitrogen removal from a bubble is 542 mmHg.

If the diver with the bubble ascends to 2 ATA pressure, the gradient will be:

$$\Delta PN_2 = 1520 \text{ mmHg}(1\text{-}0.78) + 47 \text{ mmHg}(0.78) - 133 \text{ mmHg} = 223 \text{ mmHg}$$

Thus, by moving from 4 to 2 ATA pressure, the driving gradient for nitrogen removal from the bubble is reduced by more than half. Solutions similar to Hill's can be arrived at using the alveolar gas equation, and by considering bubble and arterial inert gas tensions. In other words, Hill's solution is reasonable based on other approaches to the question.

It is also important to understand how increasing the oxygen window affects gas removal from bubbles. Because the partial pressure of oxygen falls markedly from arterial to venous blood, increasing the oxygen window will allow a larger "vacancy" for nitrogen to occupy in the bubble. Using the above example at 4 ATA, assume that the breathing gas is switched to 36%O_2/64% N_2 at 4 ATA, then the solution becomes:

$$\Delta PN_2 = 3040 \text{ mmHg } (1\text{-}0.63) + 47 \text{ mmHg}(0.64) - 133 \text{ mmHg} = 991 \text{ mmHg}$$

Thus, by increasing the oxygen in the breathing mix, the oxygen window is increased, and the gradient for nitrogen removal is increased from 542 mmHg to 991 mmHg.

Deep stops are likely beneficial because they limit the reduction in pressure and tissue supersaturation, most likely limiting bubble formation. However, deep stops are also beneficial because the pressure gradient for inert gas removal from bubbles (which we know occurs) is actually greater on deep stops than during shallower stops. This is because the bubble has to exist at ambient pressure, so as ambient pressure falls, the gradient for inert gas removal from the bubble also falls.

9.5 Decompression Profiles

Assuming that deep stops are done efficiently, the next important consideration is the subsequent, and perhaps more problematic, phase of the decompression: the middle or intermediate stops. Realistically, what concerns guide the middle portion of the decompression are similar to those that limit decompression in general. Because most would agree that bubbles are a negative link in a chain of events that results in DCI, it is important to try and reduce and/or eliminate bubble formation. Several theories strive to manage bubbling; it may even be theoretically possible to have a "no bubble" dive. However, since a "no bubble" profile would result in exceedingly long decompressions, divers usually accept the risk (or likely, the reality) that some bubbling will occur while diving. Assuming this is true, the most pressing question would then be to decide where in the decompression profile bubbling would be most hazardous. For example, bubbles formed at depth could grow and become dangerously large, impeding circulation more directly and/or for a longer time. The longer divers wait to accept a greater bubbling risk, the longer the decompression profile will become (due to necessarily longer stops and their resulting decompression obligations). If the risk of bubbling were accepted and shifted to the intermediate or shallow depth range, the impact may result in less damaging bubbling, while still enabling the diver to follow an accelerated decompression.

The argument here is that long intermediate stops, those required by conventional decompressions, cause an accumulation of gas that disproportionately adds to the required decompression. This is particularly true on very long dives. Dives carried out in a wide variety of environments by GUE and WKPP divers, among others, call into question the validity of the early models. While these experiments have been particularly successful, their decompression times result in high theoretical compartment pressures, with M-values above those acceptable by conventional wisdom. By way of illustration, gradients in the area of 85% of M-values are thought to be conservative and produce very low statistical risk of DCI. As one climbs above 90%, things become progressively more risky. Most of these experimental schedules range around 95%, with a surfacing percent commonly above 100%, and some profiles above 115%. Conducted in this way, the shorter middle section of the decompression might theoretically allow reduced shallow decompression stops. This process has been very successful, greatly reducing decompression obligations. Nonetheless, the reader must bear in mind that this process is still experimental, with a very small sample size.

9.6 What is Wrong With The Traditional Haldanean Decompression Model

J.S. Haldane started decompression modeling with the very specific goal of reducing DCS and/or enabling workers to operate under elevated pressures. In many ways, Haldane was very successful, greatly reducing DCS incidence. During this time and for many years later, Haldane's tables "worked" and were widely embraced. To some extent these tables worked too well, as divers were now able to significantly extend previous times and depths. These more aggressive profiles resulted in an increased risk of DCS and led to modifications of the Haldanean parameters. This process had been repeated many times over the years by a range of researchers and modelers. In many ways, these modifications succeeded in reducing DCS risk and extending the diver's range. In the end, one could argue that these modifications did not necessarily reflect "scientific truth", but rather produced results that were continually adjusted until a best fit occurred.

The answer to the question, "Why does Haldane's model bring one up too quickly?" can be found in his primary hypothesis. Haldane operated under several basic assumptions, the most relevant to this discussion being his assertion that decompression should allow for the maximum gradient. This premise, which recommends establishing a maximum gradient, is sound, but not nearly refined enough for proper decompression. The desire for maximum gradients led/leads to tables that bring a diver rapidly near the surface for a shallow first stop. Current thinking is that maximizing the gradient in this manner seems to encourage the growth of bubbles that negatively impact the entire decompression.

Often, when one discusses the “failure” of these tables, one is not necessarily referring to a high incidence of DCI. The success or failure of the Haldanean model can be evaluated in a number of other ways. For example, empirical research suggests that a Haldanean profile leaves one feeling more tired and with minor aches (also know as subclinical DCS). Furthermore, rapid ascents to a shallow deco stop may actually extend the amount of decompression necessary. Statistically, this decompression could be considered “successful”. However, experience indicates that the more one pushes these “limits,” the more suspect the Haldanean model appears.

9.7 Unconventional Decompressions

Many divers are led to believe that from a decompression standpoint, helium diving is dangerous and difficult. Overcoming these misconceptions frees divers to look at the application of helium in a variety of areas. Jarrod Jablonski and George Irvine were two of the earliest pioneers in the common use of helium mixtures in unconventional situations, e.g. shallower than 100 feet (30m). Lengthy decompression obligations from bottom times in excess of six hours at 300 feet led to an examination of nitrogen complications. An analysis of these diving profiles revealed that, particularly on long immersions, the true difficulty in decompression efficiency was the removal of nitrogen from slow compartments. During these dives, nitrogen is particularly troublesome because decompression time spent from 150 feet (45m) to the surface becomes so extensive that divers accumulate substantial nitrogen loads. During these long immersions, Jarrod Jablonski began successfully diving with helium-enriched decompression gasses all the way to 30 feet (10m).

As a result of their analysis of the data, GUE and WKPP divers started to radically reduce decompression time, particularly near 100ft (30m), convinced that the intermediate decompressions caused a significant accumulation of gas that would then have to be eliminated. Given their experience, these explorers are convinced that popular dissolved gas models (such as Haldane and Buhlmann) are inaccurate and produce inefficient decompressions. These models treat helium in a highly conservative manner, further highlighting the problems with dissolved gas models.

When doing very long deep dives with elevated helium mixtures, even dissolved gas decompression models demonstrate reduced decompression obligation. This is because the elevated off-gassing rate of helium is particularly favorable for such long dives. However, shorter dives, i.e. in the 20-30 minute range, are more problematic. For example, calculated decompression for 30 minutes at 300ft (90m) with no helium results in about 10 minutes less decompression than with helium in both Nitrox mixes, and about five minutes less than with helium in the 120 foot decompression bottle. It is likely that this additional time is not an accurate reflection of reality, and that new bubble models, such as the Varying Permeability Model (VPM), demonstrate more realistic parameters.

It may be that helium is treated too conservatively, and that it is either able to be eliminated more rapidly and/or is tolerated at higher pressure. Over the years, leading divers and researchers have become progressively more convinced that helium is a much better gas than previously thought. New diving efforts are highlighting a notable change in the common gasses breathed, as well as the shape of decompression profiles.

Chapter 10

Dive Planning

10.0 Introduction

Individuals often claim that dives in different environments have little relation to one another. Undoubtedly, some diving practices are environment specific; for example, those required for diving a 20ft (6m) ledge would be different from those required on a dive along a 400ft (120m) deep wreck, especially in heavy current and freezing water. However, the fundamental components of dive planning are nearly identical across a wide range of diving environments. Variable risks attributable to wreck diving may change from those found while cave diving, but fundamental concepts like air management, contingency planning, gas selection, and team coherence are similar, and largely determine the safe parameters of a given exposure.

The following discussion should help divers identify certain key elements in dive planning. A more detailed discussion of planning logistics follows. This combination, along with individual experience, will facilitate dive planning in a wide range of environments. Obviously, individuals must use this information along with local authority, personal experience, and common sense to prepare for dives in new environments.

10.1 Pre-Dive Preparation

The rewards and hazards of every diving venture require that the dive team develop a comprehensive, yet flexible, dive plan well in advance of their entry into the water. Contrary to what the term “dive planning” might suggest, dive planning involves much more than simply laying out a path for a dive team to follow. A dive team equipped with a dive plan is much more capable of dealing with unexpected challenges and preventing small problems from mushrooming into serious ones, thus enjoying the dive. Research, logistics, physical training, testing equipment, reviewing emergency procedures, and finalizing the dive plan prior to entering the water all help prevent the majority of problems from ever occurring.

10.1.1 Prior to the Trip

The first step in organizing a dive trip is the information gathering process. One must first pick a desired site, and then collect information about that site. For example, what season is the best to dive this site? What season is the worst? What kind of equipment does this site require? What level of experience? If divers who lack the requisite experience are included on the trip, is there anything else for them to do? Additionally, divers should seek to establish whether there are suitable and available accommodations nearby, and whether the transportation requirements are clear and well-organized. Divers should also evaluate what equipment and spare parts the trip requires,) and whether, and at what cost, those items can be either rented or purchased. Having the necessary information before traveling to a far away location can greatly help to ensure that the experience will be a truly positive one. This information can then be used to formulate a comprehensive dive plan, such as the one discussed below.

10.1.2 Arriving at the Dive Site

Divers should always conduct a general site survey. This will hopefully verify pre-trip information and may involve evaluation of boat diving or land-based excursions. During this survey, the team should also verify water conditions, diving logistics, and emergency procedures. On land-based excursions, divers should choose entrances that are convenient and which provide a reduced risk of spoiling visibility or of damaging the environment. In addition, divers should choose a convenient location to assemble their equipment. Equipment is usually easier to carry when assembled and transported on one's back.

10.1.3 Prior to the Dive

Following the general site survey, the team should assemble their equipment, usually leaving suit donning for last. The team should then discuss what equipment is needed, ensure that all members agree upon placement, and check for equipment failures. At this time, lights and regulators should be checked for functionality, while items like reels or lift bags should be examined to see if they are in good working order. Furthermore, this is the time when the team should discuss the dive plan in detail and verify that everyone is comfortable with the proposed dive. Teams should remember that all dives must take into account the diver with the least experience and should avoid plans that are too goal-oriented or which fixate the team on a single objective.

10. 2 Building a Dive Plan

The following dive planning outline should help divers identify the key components of a sound dive plan. Coupled with individual experience, this outline should facilitate dive planning in many different environments. Obviously, individuals preparing for dives in new environments must use this information alongside information gleaned from local authorities, personal experience and common sense.

Dive Planning Overview

- Define Dive Objectives
- Identify Risk
- Arrange Logistics
- Establish Parameters
- Assign Responsibility
- Establish Contingency Plans
- Evaluate Equipment
- Consider Nutritional Requirements

10.2.1 Define Dive Objectives

Goal-oriented diving is a reality in most forms of diving; pretending otherwise merely prevents one from safely preparing for a dive. Nonetheless, divers must prevent goals from undermining common sense and realistic dive parameters; they must always remain aware of their limitations and of the risks inherent in the projected dive.

Goal-oriented diving can increase a team's risk if divers fixate on the goal and ignore the safety parameters regulating the dive in question. For example, a diver focused on getting to a certain point in a wreck might ignore or cheat on his/her designated gas supply, and place him/herself and the team at greater risk.

Objectives can be as simple as enjoying a shallow reef or as complex as exploring miles of new cave. In either case, divers must acknowledge what they hope to get out of the dive and agree that anytime a stated objective compromises the team's safe return, that objective will be abandoned.

10.2.2 Identify Risk

Few concepts are as relative to individual preference and ability as the concept of acceptable risk. Individuals enjoy a wide range of permissible risk in both diving and life. For some, very little risk is acceptable; for others, the greater the risk the more desired the pursuit. Properly defining risk is the most important part of dive planning. Yet this essential component is often ignored and usually undervalued. Once a team has established its diving objectives, it must evaluate the degree of inherent and artificial risk associated with the planned excursion.

Inherent risk identifies the dangers that are inseparable from the activity pursued. For example, overhead diving requires individuals to recognize that a direct ascent to the surface is impossible, and that all dive planning must account for the increased risk of this limitation. On the other hand, artificial risks include dangers that are either created by divers themselves or are inherent problems that are not properly managed by the dive plan. For example, the inherent risk of overhead diving can be mitigated with proper training, responsible breathing gas limitations, proper equipment, and a sensible dive plan. Alternatively, this risk becomes amplified by improperly addressing these components. Very often divers are their own worst enemy with respect to the danger of a given dive.

Few divers invest the proper energy or thought into assessing the inherent risks of a given dive. On the contrary, they are often oblivious to them. Consider, for example, industry standards for labeling diving cylinders containing mixtures other than air. Divers are asked to clearly label their cylinders with markings like "NITROX" or "TRIMIX". The assumption here is that the primary risk lies in the use of these gasses. This is, in fact, untrue. In reality, the gasses present no risk; the risk exists entirely in *where* (what depth) these gasses are used. One "NITROX" mix might be used safely at 30ft (9m) while another "NITROX" mix might be used safely at 100ft (30m). However, a 30ft (9m) Nitrox mix would quickly result in an oxygen seizure, and a likely fatality, if used at 100ft (30m). In this situation, and many others like it, the misidentification of actual risk not only fails to reduce risk, but also actually amplifies it[1] .

Notable areas of risk assessment that commonly lead to problems include, but are not limited to, the following: improper use of gas mixtures, inefficient use and placement of diving equipment, irrational fear of decompression sickness, overly casual concern for CNS oxygen toxicity, poor recognition of the value of proper experience/training, and sloppy management of contingency planning ranging from separation to inadequate breathing supplies. These areas become problematic when individuals seek to protect themselves against sources of irrational fears, all the while creating the conditions for the emergence of a legitimate threat. For example, divers may have an irrational fear of decompression sickness; this could result in the misapplication of high oxygen mixtures, the practice of inordinately long decompressions (which can leave divers exposed in hostile environments), or the misuse of too many decompression mixes (creating greater oxygen risk and task loading). Improper dive planning or contingency arrangements might also leave divers stranded at sea and/or without sufficient breathing supplies.

1 See section 6.7 for information on proper tank labeling.

Another important part of risk assessment is identifying individuals who share similar levels of awareness, motivation, risk acceptance, and diving proficiency. This is because for divers with limited proficiency, shallow reef diving can be more dangerous than a deep wreck dive would be for divers with proper experience. All diving has a component of risk. Thus, dive planners and those who dive with them must identify that risk, and strive to reduce the potential that they are placed in unnecessary peril. In most cases, diving can be accomplished with very low levels of risk. However, low levels of diver proficiency, poor planning, and the careless use of advanced technology, among other things, elevates the risk of an otherwise simple diving activity.

The risk of a particular dive usually has less to do with the dive itself than it has to do with the planning, ability, and experience of the participants. In other words, people generally create their own problems by not properly managing or identifying a dive's true risks. Learning realistic risk analysis is the single most important component to proper dive planning. It is impossible to craft a reasonable and safe dive plan without first identifying the actual risks of a proposed activity. While gaining experience with risk identification, divers are encouraged to list all possible risks and to rate them in terms of the degree of threat those risks pose to a diver's life.

Proper dive planning should either reduce or eliminate these risks. Measures that do not directly reduce or eliminate these dangers should be abandoned, while emergency procedures and contingency planning should properly support risks that cannot be eliminated. Generally speaking, any irresolvable problem that arises from less than three failures (equipment or action) is not properly managed. For example, a scooter failure would result in a diver being towed (one problem) while two scooter failures would result in divers swimming (two problems). If the distance to the exit is too far to swim (third, irresolvable, problem), then the team did not plan properly for this dive; they should have towed a safety scooter.

10.2.3 Diving Logistics

Logistical operations primarily concern how divers experience a given dive site, and by what means that experience will be achieved. Divers commonly operate from boats, but they can also operate from automobiles, as with spring and lake diving. Furthermore, divers may also use underwater propulsion vehicles, which further impacts logistical concerns.

The logistics of a particular dive can vary substantially from one location to another. All dive planning should include elements that maximize safety, i.e. sufficient support, gas supply, and contingency/emergency planning.

In many cases, diving leaders take on much of the responsibility for logistical planning. Unfortunately, this lulls many divers into a false sense of security, one in which they lack a realistic appreciation for dive planning or risk. Divers must become practiced at logistical planning, and should never blindly trust arrangements made by others.

10.2.4 Establish Parameters

Diving parameters can be established by an array of constraints that vary in their relevance to any given dive. The risk of a particular dive is often greatly magnified, if not created, by the lack or avoidance of appropriate diving parameters. Fatal accidents are replete with divers that failed to establish sensible limitations or ignored established parameters, resulting in insufficient breathing gas, extended decompression obligation, team and/or support vessel separation. All parameters, including time limitations, should be set from a consideration of worst-case scenarios.

10.2.4.1 Time

Individuals must define when in the day the diving activity will take place, and agree upon an acceptable bottom time limit. Certain dives, such as those in the ocean, might have to be cancelled should it become too late in the day. This is because finding a team lost at sea increases exponentially in difficulty with reduced ambient light.

Bottom time limits will largely correspond to the experience of team members, the diving environment, and the time of day established for diving activity. For example, divers uncomfortable with decompression diving have predetermined limits set by the planned diving depth. In contrast, decompression divers are limited by acceptable decompression time. Divers who are new to decompression should proceed gradually, adding longer decompression times as they become more comfortable.

Environmental instability, such as in ocean diving, also limits the accumulation of both acceptable bottom time and decompression exposure. Dives in the ocean should generally not exceed 90 minutes of immersion, because there is risk that environmental changes (weather, current, etc.) will severely compromise team safety. Dives that exceed this exposure, while exposing the team to greater levels of risk, require substantially greater commitment and support.

The length of a particular dive may also be impacted by other factors, such as thermal requirements, DPV burn time, breathing supply, and lighting requirements. For example, divers should leave a 20 percent reserve on their primary light, while each back up light should allow them to exit from maximum penetration (i.e. two reserve and one primary). Furthermore, divers should be very familiar with their DPV battery burn time to ensure that in the event of DPV failure, an exit can be managed. In the case of breathing supply, most technical divers maintain two thirds of their supply for diving (one third for each direction) and one third for emergencies.

10.2.4.2 Depth

The expression "deep diving" is meaningless outside the context of individual experience and team preparedness. However, dives exceeding 100fsw (30msw) require progressively greater levels of experience and preparation. Furthermore, beyond, and in many cases near, 100fsw (30msw), divers should use helium-based mixtures to eliminate the onset of narcotic impairment. Trying to go much beyond these depths while air diving has become indefensible today.

Mixed gas diving has all but eliminated the most obvious risk to deep diving, and, among most sensible divers, has greatly reduced risk. However, deeper mixed gas diving creates an array of other risks, such as decompression obligation, time limitations, breathing gas supply, and ascent limitations. Deeper diving is similar to overhead diving in that to resolve problems, divers cannot merely ascend to the surface. Therefore, these divers must be well-versed in the mechanics of depression diving, and be prepared to manage problems efficiently.

Deeper dives also require more attention to meeting established time limitations. This is because lost minutes can result in exponential decompression, which greatly impacts breathing supply requirements. Many divers have set up insurmountable obstacles for themselves by extending their time at depth without reserve supplies or contingency plans.

10.2.5 Assign Responsibility

For the fun and safety of the diving group, all dives require that certain members conduct certain tasks. Some of these tasks are the responsibility of one diver for the benefit of the group, such as towing a surface float or running a guideline in an overhead. Other tasks require the commitment of every team member, such as air management and team unity. Regardless of individual or assigned team responsibilities, divers should be able to function in all necessary capacities.

10.2.6 Contingency Planning

Properly crafted dive plans account for contingencies like unplanned extensions in bottom time, extensions in decompression obligations and separation from a diving support vessel and/or dive team. Contingency planning should also involve preparation to handle emergency situations like decompression sickness, lost divers, etc.

10.2.7 Evaluate Equipment

All divers should be very familiar with individual, team, and emergency equipment. However, leading explorers long ago recognized that true familiarity with another diver's equipment was difficult without standardized configurations. This consideration is one of the mainstays of DIR (Doing It Right) diving, which promotes team standardization as a key component of team/individual safety.

10.2.8 Nutritional Requirements

Unfortunately, most divers ignore proper nutrition, especially when they are traveling on a dive trip. Nonetheless, diving can lead to fatigue and may require sudden heavy exertion, i.e. while swimming against a strong current. Divers who are poorly nourished may find themselves unable to meet these challenges. Individuals should be well-nourished and, especially, well-hydrated before diving.

10.3 Dive Planning Components

Dive planning includes generating decompression tables, choosing the right gas mixes, oxygen planning, and narcosis levels, and establishing breathing gas parameters.

10.3.1 Decompression Table Generation

All dive tables must include a table with the expected decompression, plus and minus at least 30% for depth and time. Divers should study these tables so they can evaluate the trend of the decompression should they need to extrapolate from it.

Divers should also generate contingency tables to enable them to adjust their decompression schedule in the event of a lost or nonfunctional decompression bottle. They should be able to adjust their decompression with any combination of gasses. For example, a diver who loses their oxygen bottle should be able to do the entire decompression on 50% Nitrox.

Experienced divers are able to extrapolate from a memorized table to any reasonable schedule they may encounter. Skilled divers learn to make minimal use of written decompression tables; instead they focus on understanding how the tables are generated, and invest time in understanding the decompression curve and how it is reshaped by alterations in the plan (lost gas or increased time/depth).

10.3.2 Choosing the Right Gas Mixes: Standardized Mixtures

Many divers have been led to believe that great precision is necessary when calculating a "best mix" for a particular dive. In truth, such mixtures do not markedly improve a diver's efficiency, but rather can place them at greater risk as they near individual limitations. In contrast, standard mixes allow divers to become familiar with a handful of gasses that provide them with very similar efficiency. This familiarity, coupled with a more liberal safety margin, makes the following mixtures a wise choice for nearly any diving operation.

10.3.3 Oxygen Planning and Narcosis Levels

Because oxygen and nitrogen are narcotic gasses and induce gas narcosis, dives that induce elevated PO_2's and/or END's increase risk and reduce efficiency. Thus, all breathing gasses should maintain a PO_2 of less

TABLE 10.1 BOTTOM MIXES

Depth (Feet)	Depth (Meters)	Mix
1' - 100'	1m - 30m	32% O_2*
110' - 150'	33m - 45m	21/35 (O_2/He)
160' - 200'	48m - 60m	18/45 (O_2/He)
210' - 250'	63m - 75m	15/55 (O_2/He)
260' - 400'	78m- 121m	10/70 (O_2/He)
*Divers with proper training and experience may opt for the use of 32% oxygen/ 30% helium to reduce physiological stress and eliminate narcosis.		

TABLE 10.2 DECOMPRESSION MIXES

Depth (Feet)	Depth (Meters)	Mix
20'	6m	100% Oxygen
70'	21m	50% Oxygen
120'	36m	35/25 (O_2/He)
190'	57m	21/35 (O_2/He)

than 1.4, and an equivalent narcotic depth of less than 100fsw (30msw).

Where deviations from standardized mixes are necessary, it is better to maintain higher helium and lower oxygen content. For example, operations that, over the course of a couple days, do not allow for mix fills, would find divers breathing a stage and topping the back gas with air. This practice is only reasonable when helium is proportionately higher and oxygen content moderate. Oxygen toxicity is rarely survivable; therefore, pushing the oxygen content is never wise.

10.3.4 Establishing Breathing Gas Parameters

Most of the calculations relevant to breathing gas parameters are illustrated by the *T formula* discussed in Chapter 5. For example, planning a dive to 170fsw (52msw) results in the following calculation:

1. Establish the maximum acceptable oxygen percentage considering a 1.4 PO_2:

    FG= 1.4 PO_2/ATA results in a maximum of 22.8%

    22% shows limited benefit over the standard mix of 18/35 for 170fsw

    Established standard mix PO_2=FG x ATA results in a PO_2 of 1.1 giving divers a greater margin for error with dives of greater exertion, cold, etc.

Note: Calculating the Maximum Mperating Depth of a gas percentage when given the oxygen PO_2 is done by dividing that PO_2 by the fraction of oxygen. For example, assuming a maximum acceptable PO_2 of 1.2, a 22% oxygen mix will reach this PO_2 at a depth of 147fsw (45msw) (1.2 PO_2/. 22 = 5.46 ATA or 147fsw.

2. Establish a mixture that produces an Equivalent Narcotic Depth of 100fsw (30msw)

    Air at 100fsw (30msw)= 4ATA of narcotic gas (assuming that oxygen and nitrogen are equally narcotic)

    FG= PNG (total pressure of narcotic gas)/ATA calculates the fraction of oxygen and nitrogen allowed in the mix at calculated depth of 170fsw (51msw) which equals 65%

    Therefore the balance of 35% must constitute non-narcotic helium

    The standardized mix of 45% allows good leeway on this calculated mixture

Note: Assuming a given or desired oxygen PO_2, calculating the narcotic impact of a particular mix at a given depth is merely a matter of taking the potential narcotic gas partial pressure and relating it to an equivalent air depth. For example, assume a mixture of 21/25 at 170fsw (51msw). 100% (constituent gasses) – 25% helium (assuming that oxygen is narcotic) = 75% potentially narcotic gas. This, multiplied by 6.15 ATA, results in a narcotic partial pressure of 4.61 (.75 x 6.15). Therefore, assuming oxygen is narcotic, this mixture has an equivalent narcotic depth of 119.25fsw (36msw).

10.4 Nitrox Mixing Mathematics

How much additional oxygen is needed to make 50% Nitrox at a pressure of 3,000psi?

Formula: FO_2 - .21/. 78 x 3000psi results in 1,101 psi of additional oxygen

In order to create this mixture by partial pressure blending, a technician would have to:

1. Drain bottles
1. Add 1,100psi of oxygen
2. Top off with air to 3,000psi
3. Analyze mixture

Assuming the tanks contained a previous mixture, the technician would:

1. Determine the total oxygen needed in the mix with a given or desired $FO_{2.}$
2. Determine the amount of oxygen remaining in the gas present in mix before topping off.
3. Subtract 1-2= Balance of O_2 needed
4. Adjusted FO_2 = Balance O_2 needed (3) Divided by PSIG to add
5. ((Adj. FO_2 - .21)/ .78) * PSIG to add = O_2 to be added

For example, the desired mix is 50% Nitrox with a 3,000psi fill; remaining in the cylinder are 2000psi of a 35% Nitrox mix.

1. Total Needed oxygen: .50 x 3000psi = 1500psi oxygen
2. Oxygen present in mix: .35 x 2,000psi = 700psi oxygen
3. Remaining oxygen needed: 1,500psi O_2 – 700psi O_2 = 800psi O_2
4. Adjusted FO_2: 800psi oxygen needed out 1000psi to add = 800/1000

   = .80 - .21 / .79 * 1000psi = 746.8psi
5. Oxygen to be added= 746.8psi

10.5 Trimix Mixing Mathematics

What gasses are necessary to make an 18/45 Trimix mixture?

1. Determine the helium that must be added to the mix.

   (FHe x Pt)= .45 x 3000psi = 1,350psi He
2. Determine total oxygen that is needed for this mix.

   (FO_2 x Pt)= .18 x 3000psi = 540psi oxygen
3. Determine total gas to be added on top of helium.

   (Pt – P He)= 3,000psi – 1,350psi He = 1,650psi

4. Determine adjusted $FO_{2.}$

   (Total O_2 from step 2) / (total gas to add from step 3)

   540psi / 1,650 = 33%

5. Determine oxygen to add to mix.

   (Adjusted FO_2 - .21/ .78 x gas to be added

   .33 - .21/ .78 x 1,650 = 250psi oxygen to add to mix

Typically, first adding helium to an empty tank, then adding oxygen, and then lastly topping it off with air would make this mixture. This process allows the more expensive helium to be added at lower pressure. Furthermore, analog gauges are less reliable at the low end near zero, making a small amount such as 250psi easier to add when starting from higher pressures.

10.5.1 Topping Off a Partial Trimix Fill With Air

Assume a mix of 18/45 with 2,000psi that is to be topped off to 3,000psi. What is the new mix?

1. Determine present amount of He in mix.

   (FHe x remaining psi in tank)= .45 x 2,000psi = 900psi He

2. Determine adjusted fraction He.

   He in psi in current mix / total psi to be in mix

   900/3,000 = 30%

3. Determine amount of oxygen in present mix.

   (FO_2 x psi) .18 x 3,000= 360psi

4. Determine amount of air to add to mix.

   (Total psi – psi to be added)

   3,000 – 2,000 = 1,000psi

5. Determine oxygen in air to be added to mix.

   (.21 x psi to be added)

   .21 x 1,000psi = 210psi oxygen

6. Determine adjusted $FO_{2.}$

   (Total O_2 needed + O_2 present in mix) / total psi

360psi + 210psi = 570psi oxygen/3,000psi results in a 19% O_2 mixture

This mix would be a 19/30.

10.5.2 Adjusting a Mix from a Remaining Mixture

Assume a mix of 21/35 at 2,000psi remains; from this an 18/45 mix at a pressure of 3,000psi is desired

1. Determine psi of He in present mix.

   (FHe x psi) = .35 x 2,000psi= 700psi

2. Determine He necessary for new fraction of He.

   (Target FHe x total fill pressure) = .45 x 3000 = 1,350psi He

3. Determine amount of He needed to adjust.

   (Target He psi – He psi in present mixture)

   1,350psi – 700psi = 650psi He to add to mix

4. Determine amount of oxygen to be added to final mix.

   (FO_2 x total psi)= .18 x 3000psi results in 540 total psi O_2needed

5. Determine amount of oxygen present in mix.

   (Present FO_2 x existing psi)= 420psi oxygen

6. Determine amount of gas to add to mix.

   Total fill pressure psi – (He to add + existing psi in tank)

   3,000psi – (2,000 + 650)= 350psi to add to mix

7. Determine adjusted $FO_{2.}$

   a. Value from step 4 (540psi) – O_2 psi in step 5 (420psi) = 120psi O_2

   b. Value from step a (120psi) / value from step 6 (350psi)

   = 120/350 results in a 34% mixture

8. Determine oxygen to add.

   (Adjusted FO_2 - .21 / .78 x psi from step 6 = 57psi O_2 to add)

Note: These calculations allow for minor modifications, and for a better understanding of mix manipulation; however, individuals should be aware that adjusting mixtures in the above manner becomes increasingly problematic. Divers can only accurately measure oxygen percentages, not helium percentages. If there is any question regarding sufficient helium content, divers should remix from empty tanks.

10.6 Decompression Considerations

Choosing decompression mixtures is based primarily on doing a cost/benefit analysis. Individuals must assess the difficulty and logistical feasibility of carrying a particular set of decompression gasses against the benefits derived from these gasses. For example, using a variety of decompression gasses may reduce "calculated" decompression, but it will increase task loading and fatigue.

Furthermore, trying to maintain high partial pressures of oxygen with multiple mixtures results in vasoconstriction (a reduction in off-gassing potential), increased pulmonary irritation (likely with reduced diffusion efficiency), and increased CNS toxicity risk. Sensible divers vary gas mixtures by weighing the benefit of each gas introduced against the "cost" of doing so. For example, a diver will quickly see that in a 150fsw (45msw) dive, using oxygen and 50% Nitrox is more than sufficient for efficient decompression, while adding 35% to these has a negligible impact on decompression but adds additional drag, weight, and risk.

Divers can enter various standard mixes into a conventional decompression program like GUE's DecoPlanner to evaluate the benefit of additional decompression mixes. Bottom mixes with low oxygen PO_2's and low equivalent narcotic depths, should provide divers with a good margin of safety. The common 1.4 PO_2 should be considered the maximum permissible, and divers should choose from established standard mixes to provide for better safety margins.

10.6.1 Cylinder Choices

Stage bottles used for decompression should provide ample gas, but should not be overly large or heavy. Aluminum cylinders are the cylinder of choice for most diving and are mandatory in the ocean where heavy cylinders can dangerously overweight a diver. Decompression cylinders should be near neutral (a bit negative when full, a bit positive when empty).

Except in cold water where very buoyant dry suits are required, double tanks should be similarly weighted. In the case of cold water diving, steel tanks can offset the increased buoyancy caused by thick undergarments. Nonetheless, all divers should be able to swim against the negative weight of their equipment while being able to remain on a decompression stop at 10ft (3m) with nearly empty tanks.

10.6.2 Travel Mixes

Travel mixes are sometimes used for dives that involve lengthy travel, or as a means to get to deeper depths without consuming a potentially hypoxic mix near the surface. The primary purpose of a travel mix is to provide a PO_2 that will sustain divers in cases where the bottom mix PO_2 is low enough to create the risk of unconsciousness. When the diver is safely out of the hypoxic danger zone (near .15), then s/he switches to the bottom mix and continues the descent. However, for most applications, the deeper decompression gas is used as a travel mix.

10.6.3 Thermal Conductivity

Helium-based mixtures contribute significantly to heat loss when divers are immersed in it, as in the case of dry suit inflation. Helium transmits heat very efficiently, with a thermal conductivity six times that of air. Divers should never fill suits with helium-based mixtures, as the risk for hypothermia and mental impairment are significant. Argon is the preferred gas for suit inflation, with air still being far preferable to helium mixtures for this application. Individuals should not underestimate the thermal loss that can result from helium mixes, or the subtle, but dangerous, impairment of hypothermia.

Helium is six times more thermally conductive than compressed air; this is why divers should always use an auxiliary gas for suit inflation. Air is certainly better than helium for suit inflation, but argon has heat transfer capacity that is about 66% that of compressed air. Though carbon dioxide also has a low heat conductive capacity when moisture is present, it can cause skin irritation from carbonic acid, making argon a better choice.

TABLE 10.3 FILL CHART: IMPERIAL

Pressure (bar)

O2	He	10		20		30		40		50		60		70		80		90		100		O2	He
10	90	1	9	2	18	3	27	4	36	5	45	6	54	7	63	8	72	9	81	10	90	10	90
10	70	0	7	1	14	1	21	2	28	2	35	3	42	3	49	4	56	4	63	5	70	10	70
15	55	1	6	1	11	2	17	3	22	4	28	4	33	5	39	6	44	6	50	7	55	15	55
18	45	1	5	2	9	2	14	3	18	4	23	5	27	6	32	7	36	7	41	8	45	18	45
19	35	1	4	1	7	2	11	3	14	3	18	4	21	5	25	5	28	6	32	7	35	19	35
21	35	1	4	2	7	3	11	4	14	5	18	6	21	7	25	7	28	8	32	9	35	21	35
30		1	0	2	0	3	0	5	0	6	0	7	0	8	0	9	0	10	0	11	0	30	
30	30	2	3	4	6	6	9	8	12	10	15	12	18	14	21	15	24	17	27	19	30	30	30
32		1	0	3	0	4	0	6	0	7	0	8	0	10	0	11	0	13	0	14	0	32	
35		2	0	4	0	5	0	7	0	9	0	11	0	12	0	14	0	16	0	18	0	35	
35	25	2	3	5	5	7	8	10	10	12	13	15	15	17	18	19	20	22	23	24	25	35	25
50		4	0	7	0	11	0	15	0	18	0	22	0	26	0	29	0	33	0	37	0	50	
50	25	4	3	9	5	13	8	17	10	22	13	26	15	30	18	35	20	39	23	43	25	50	25
50	50	5	5	10	10	15	15	20	20	25	25	30	30	35	35	40	40	45	45	50	50	50	50

O2	He	110		120		130		140		150		160		170		180		190		200		O2	He
10	90	11	99	12	108	13	117	14	126	15	135	16	144	17	153	18	162	19	171	20	180	10	90
10	70	5	77	6	84	6	91	7	98	7	105	7	112	8	119	8	126	9	133	9	140	10	70
15	55	8	61	8	66	9	72	10	77	11	83	11	88	12	94	13	99	13	105	14	110	15	55
18	45	9	50	10	54	11	59	11	63	12	68	13	72	14	77	15	81	16	86	16	90	18	45
19	35	7	39	8	42	9	46	9	49	10	53	11	56	12	60	12	63	13	67	14	70	19	35
21	35	10	39	11	42	12	46	13	49	14	53	15	56	16	60	17	63	18	67	19	70	21	35
30		13	0	14	0	15	0	16	0	17	0	18	0	19	0	21	0	22	0	23	0	30	
30	30	21	33	23	36	25	39	27	42	29	45	31	48	33	51	35	54	37	57	39	60	30	30
32		15	0	17	0	18	0	19	0	21	0	22	0	24	0	25	0	26	0	28	0	32	
35		19	0	21	0	23	0	25	0	27	0	28	0	30	0	32	0	34	0	35	0	35	
35	25	27	28	29	30	32	33	34	35	37	38	39	40	41	43	44	45	46	48	49	50	35	25
50		40	0	44	0	48	0	51	0	55	0	59	0	62	0	66	0	70	0	73	0	50	
50	25	48	28	52	30	56	33	61	35	65	38	69	40	74	43	78	45	82	48	87	50	50	25
50	50	55	55	60	60	65	65	70	70	75	75	80	80	85	85	90	90	95	95	100	100	50	50

O2	He	210		220		230		240		250		260		270		280		290		300		O2	He
10	90	21	189	22	198	23	207	24	216	25	225	26	234	27	243	28	252	29	261	30	270	10	90
10	70	10	147	10	154	11	161	11	168	12	175	12	182	13	189	13	196	14	203	14	210	10	70
15	55	15	116	15	121	16	127	17	132	18	138	18	143	19	149	20	154	20	160	21	165	15	55
18	45	17	95	18	99	19	104	20	108	20	113	21	117	22	122	23	126	24	131	24	135	18	45
19	35	14	74	15	77	16	81	16	84	17	88	18	91	18	95	19	98	20	102	20	105	19	35
21	35	20	74	20	77	21	81	22	84	23	88	24	91	25	95	26	98	27	102	28	105	21	35
30		24	0	25	0	26	0	27	0	28	0	30	0	31	0	32	0	33	0	34	0	30	
30	30	41	63	43	66	45	69	46	72	48	75	50	78	52	81	54	84	56	87	58	90	30	30
32		29	0	31	0	32	0	33	0	35	0	36	0	38	0	39	0	40	0	42	0	32	
35		37	0	39	0	41	0	43	0	44	0	46	0	48	0	50	0	51	0	53	0	35	
35	25	51	53	54	55	56	58	58	60	61	63	63	65	66	68	68	70	71	73	73	75	35	25
50		77	0	81	0	84	0	88	0	92	0	95	0	99	0	103	0	106	0	110	0	50	
50	25	91	53	95	55	100	58	104	60	108	63	113	65	117	68	121	70	126	73	130	75	50	25
50	50	105	105	110	110	115	115	120	120	125	125	130	130	135	135	140	140	145	145	150	150	50	50

Instructions: Find desired mix and pressure. Write down the O_2/He. Find the current mix and pressure. Subtract the O_2/He of the current mix from the O_2/He of the desired mix. Add fudge factors. Mix, analyze and dive! Use at your own risk, all totals should be verified by calculation and analysis of final mix.

Fudge Factors: Helium: Add 15%. Oxygen: Add 10%.

Pressure (bar)

O2	He	10		20		30		40		50		60		70		80		90		100		O2	He
10	90	1	9	2	18	3	27	4	36	5	45	6	54	7	63	8	72	9	81	10	90	10	90
10	70	0	7	1	14	1	21	2	28	2	35	3	42	3	49	4	56	4	63	5	70	10	70
15	55	1	6	1	11	2	17	3	22	4	28	4	33	5	39	6	44	6	50	7	55	15	55
18	45	1	5	2	9	2	14	3	18	4	23	5	27	6	32	7	36	7	41	8	45	18	45
19	35	1	4	1	7	2	11	3	14	3	18	4	21	5	25	5	28	6	32	7	35	19	35
21	35	1	4	2	7	3	11	4	14	5	18	6	21	7	25	7	28	8	32	9	35	21	35
30		1	0	2	0	3	0	5	0	6	0	7	0	8	0	9	0	10	0	11	0	30	
30	30	2	3	4	6	6	9	8	12	10	15	12	18	14	21	15	24	17	27	19	30	30	30
32		1	0	3	0	4	0	6	0	7	0	8	0	10	0	11	0	13	0	14	0	32	
35		2	0	4	0	5	0	7	0	9	0	11	0	12	0	14	0	16	0	18	0	35	
35	25	2	3	5	5	7	8	10	10	12	13	15	15	17	18	19	20	22	23	24	25	35	25
50		4	0	7	0	11	0	15	0	18	0	22	0	26	0	29	0	33	0	37	0	50	
50	25	4	3	9	5	13	8	17	10	22	13	26	15	30	18	35	20	39	23	43	25	50	25
50	50	5	5	10	10	15	15	20	20	25	25	30	30	35	35	40	40	45	45	50	50	50	50

O2	He	110		120		130		140		150		160		170		180		190		200		O2	He
10	90	11	99	12	108	13	117	14	126	15	135	16	144	17	153	18	162	19	171	20	180	10	90
10	70	5	77	6	84	6	91	7	98	7	105	7	112	8	119	8	126	9	133	9	140	10	70
15	55	8	61	8	66	9	72	10	77	11	83	11	88	12	94	13	99	13	105	14	110	15	55
18	45	9	50	10	54	11	59	11	63	12	68	13	72	14	77	15	81	16	86	16	90	18	45
19	35	7	39	8	42	9	46	9	49	10	53	11	56	12	60	12	63	13	67	14	70	19	35
21	35	10	39	11	42	12	46	13	49	14	53	15	56	16	60	17	63	18	67	19	70	21	35
30		13	0	14	0	15	0	16	0	17	0	18	0	19	0	21	0	22	0	23	0	30	
30	30	21	33	23	36	25	39	27	42	29	45	31	48	33	51	35	54	37	57	39	60	30	30
32		15	0	17	0	18	0	19	0	21	0	22	0	24	0	25	0	26	0	28	0	32	
35		19	0	21	0	23	0	25	0	27	0	28	0	30	0	32	0	34	0	35	0	35	
35	25	27	28	29	30	32	33	34	35	37	38	39	40	41	43	44	45	46	48	49	50	35	25
50		40	0	44	0	48	0	51	0	55	0	59	0	62	0	66	0	70	0	73	0	50	
50	25	48	28	52	30	56	33	61	35	65	38	69	40	74	43	78	45	82	48	87	50	50	25
50	50	55	55	60	60	65	65	70	70	75	75	80	80	85	85	90	90	95	95	100	100	50	50

O2	He	210		220		230		240		250		260		270		280		290		300		O2	He
10	90	21	189	22	198	23	207	24	216	25	225	26	234	27	243	28	252	29	261	30	270	10	90
10	70	10	147	10	154	11	161	11	168	12	175	12	182	13	189	13	196	14	203	14	210	10	70
15	55	15	116	15	121	16	127	17	132	18	138	18	143	19	149	20	154	20	160	21	165	15	55
18	45	17	95	18	99	19	104	20	108	20	113	21	117	22	122	23	126	24	131	24	135	18	45
19	35	14	74	15	77	16	81	16	84	17	88	18	91	18	95	19	98	20	102	20	105	19	35
21	35	20	74	20	77	21	81	22	84	23	88	24	91	25	95	26	98	27	102	28	105	21	35
30		24	0	25	0	26	0	27	0	28	0	30	0	31	0	32	0	33	0	34	0	30	
30	30	41	63	43	66	45	69	46	72	48	75	50	78	52	81	54	84	56	87	58	90	30	30
32		29	0	31	0	32	0	33	0	35	0	36	0	38	0	39	0	40	0	42	0	32	
35		37	0	39	0	41	0	43	0	44	0	46	0	48	0	50	0	51	0	53	0	35	
35	25	51	53	54	55	56	58	58	60	61	63	63	65	66	68	68	70	71	73	73	75	35	25
50		77	0	81	0	84	0	88	0	92	0	95	0	99	0	103	0	106	0	110	0	50	
50	25	91	53	95	55	100	58	104	60	108	63	113	65	117	68	121	70	126	73	130	75	50	25
50	50	105	105	110	110	115	115	120	120	125	125	130	130	135	135	140	140	145	145	150	150	50	50

Instructions: Find desired mix and pressure. Write down the O_2/He. Find the current mix and pressure. Subtract the O_2/He of the current mix from the O_2/He of the desired mix. Add fudge factors. Mix, analyze and dive! Use at your own risk, all totals should be verified by calculation and analysis of final mix.

Fudge Factors: Helium: Add 15%. Oxygen: Add 10%.

Chapter 11

Managing Breathing Gas Supplies

11.0 Introduction

Proper dive planning requires that individuals are able to accurately predict the gas they will consume during a given dive. Gas consumption varies greatly among individuals, and may vary considerably with exertion level. This is particularly true of divers who are not engaged in regular fitness regimes. More aggressive diving requires increasingly more precise determination of gas consumption. Technical diving often requires that individuals estimate their gas needs for both bottom and decompression mixes, as well as for emergencies/failures. Furthermore, an efficient calculation of gas consumption helps one to understand the dive profile and to plan for contingencies.

In order to properly calculate gas consumption at various depths, divers should establish a baseline measurement of their gas consumption. This baseline is most effectively related to the volume of gas that they would consume at the surface, allowing them to calculate what they would use at a range of depths. This baseline can be established at the surface, at a fixed depth, or by divers calculating/measuring an average depth on a common profile. It is recommended that divers use the latter two methods to establish consumption, as it tends to generate a more reliable measure of actual use (as opposed to walking around on the surface with cylinders). Divers should measure their consumption rate in a variety of environments and situations, i.e. under work and at rest, to gain a better feel for variation, and to improve planning ability.

11.1 Measuring Gas Consumption

In order to properly anticipate gas consumption, divers must establish a baseline consumption rate that is calculated at a constant depth. Divers can most easily do this by remaining at a constant depth for a fixed time, usually 10 minutes, which allows them to calculate a cubic feet (or bar) per minute consumption rate. Alternatively, divers can calculate (or estimate) the average depth of a particular dive and measure gas consumption over time. Depth averaging often gives a more realistic estimate of workload, as it represents typical diving activity. Average depth estimates can be less accurate as they approximate the average depth in a multilevel profile (unless, where available, calculations are done with an averaging meter/watch). Nonetheless, depth averaging by uncalculated estimates is a beneficial exercise because it allows divers to become experienced in estimating actual diving profiles, a valuable skill in later decompression exercises. This estimated consumption per minute rate is then referenced to the surface, allowing individuals to extrapolate to any dive/depth. Gas consumption baselines are usually called SAC rates (surface air consumption) or RMV (respiratory per minute volume).

11.2 SAC Rate Calculations

Consider the following:

If 500psi (34bar) is consumed in 10 minutes from an $80ft^3$ (11L) at 100ft (34m), what is the SAC rate?

1. Calculate gas consumed in the given time period.

500psi (34bar) consumed in 10min = 50psi (3.4bar)/min.

2. Relate gas consumed at depth to equivalent consumption at the surface.

50psi (3.4bar)/min at 4.4 ATA will be 1/4 the gas consumption for a diver at the surface.

50psi (3.4bar)/4 = 12.5psi (.85bar)/min at surface

3. Relate gas consumption to a universal volume, e.g. ft^3 (L), so that the baseline is independent of the tank used.

How many ft^3 (liters) are 12.5psi (.85bar) out of an $80ft^3$ (11L) cylinder?

Imperial: Calculating cylinder volume in cubic feet requires an awkward manipulation because U.S. cylinder size is based on an odd measuring system. Total volume of a cylinder is based upon its rated pressure. For example, $80ft^3$ tanks are $80ft^3$ at their rated pressure of 3,000psi. Therefore, to calculate the volume for various pressures, one must first divide the cubic feet by the rated pressure ($80ft^3$/3000psi= $.027ft^3$/psi), and then multiply this number by the fill pressure to establish equivalent volume in ft^3. Relating volume to ft^3 allows a direct comparison regardless of the tank used.

Given the above situation (step 2) what is the volume of air consumed in ft^3 if a diver consumes 12.5psi (.85bar) while at the surface?

$.027ft^3$/psi x 12.5psi (.855bar) = $.33ft^3$

Given a constant breathing rate, and a diver's surface air consumption (here $.33ft^3$), one can go on to measure consumption converted at any depth (see step 4).

Metric: Metric calculations are far more intuitive, as cylinder volume measurements depend upon the volume of water a cylinder will hold. For example, an 11L cylinder will hold 11L of water. These measurements are not dependant on pressure or other troublesome variables.

In the above example, (step 2) what is the volume of air consumed in free liters if a diver consumes .85bar while at the surface? To establish volume divers merely multiply bar by cylinder size.

.85bar x 11L =9.4 liters

4. Convert SAC rate baseline to a volume of air consumed on an impending dive profile.

For example:

Dive to 70ft (21m) for 30min. How much gas is required?

Imperial:

70ft is 3.1ATA x .33psi/min SAC= $1.0ft^3$/min at depth x 30 = 30.6 cubic feet consumed.

Metric:

21m is 3.1ATA x .85= 2.63 x 30=78.9 liters

SAC rates are an especially valuable way for divers to anticipate gas requirements, and to track varying consumption rates. For example, divers can monitor improvement in fitness and diving comfort by tracking changes in SAC rates. In general, divers will find that better fitness is especially valuable in times of duress or in times of exertion, as their SAC rates will remain more similar to resting rates. With practice, divers will find that they can very accurately predict their gas needs on a given dive, the result being that they greatly extend both their efficiency and safety.

11.3 The "One Third" Air Rule

Environments that allow divers to make an immediate ascent to the surface do not usually require that a large emergency gas reserve be maintained. Commonly, divers strive to return to thei dive boat with 500psi/35bar remaining in their tanks. However, as the complexity of a dive increases, so must one's attention to gas management. When a diver's ability to make a free ascent is limited or prohibited, a greater reserve of gas must be maintained. Any number of factors may limit a free ascent to the surface. Overhead obstructions, such as being in a wreck, below ice, or in a cave, are obvious barriers to an immediate ascent and thus require reserve supplies. Less obvious examples include deeper open water dives and/or decompression dives.

To maintain sufficient gas reserves, cave divers established the rule of thirds. This *Third's Rule* enables divers to easily manage their gas, while leaving ample reserves for exiting and for emergencies. In overhead diving such as cave, wreck, or ice, the initial one third is used for penetration, while the remaining two thirds are reserved for return and emergencies. While diving the Thirds Air Rule, it is essential that divers carefully monitor their gas and always maintain a sufficient volume to allow them to exit safely from the farthest point in the dive. This reserve volume also takes into account the unlikely event that a team member could experience a catastrophic gas loss at the farthest point. Ocean dives that require additional gas reserves demand that individuals begin their ascent with at least one third of their starting volume still remaining.

11.4 Gas Management With Similar Tanks

Assuming that all divers on a given team are using the same type of cylinder, the process then of calculating thirds for penetration is simple. If a diver has 3000psi, they can use 1,000psi for the dive, 1,000psi for the return and 1,000psi for emergencies. Therefore, the 3,000psi fill requires a diver to turn the dive at a pressure of 2,000psi. If the diver has a 3,100psi fill, then one third is 1,033. Rather than divide amounts less than one hundred psi, divers round their fill pressure DOWN to the first number evenly divisible by three. So, 3,100psi rounds to 3,000psi. One third of this is 1,000psi. One third of the rounded value is then subtracted from the total fill pressure. In this case, 3,100psi - 1,000psi = 2,100psi turn pressure. This thirds calculation procedure can be summarized as follows:

Determine the tank with the lowest pressure.

Round this pressure down to the first number evenly divisible by three.

Calculate one third of this adjusted volume.

Subtract this value from every diver's available pressure.

Divers often have different gas consumption and must ensure that they each have an adequate volume of gas to assist an out-of-gas team member. The team agrees on a common volume of usable gas and that no one can use more than this volume. This usable volume is based upon the diver with the least amount of gas. For example, consider a team with the same type of tank and the following fill pressures: 3,200psi, 3,100psi, and 3,300psi. The diver with 3,100psi has the lowest volume and therefore determines the gas available for penetration. First the 3,100psi is rounded down to the first value evenly divisible by three, namely 3,000psi. One third of this value is 1,000psi. All members of the team are therefore limited to 1,000psi of air for their penetration. Whoever consumes 1,000psi first must signal the team and all divers must exit. This system insures that each diver has sufficient gas for exiting and for bringing out another team member.

11.5 Dissimilar Fill Pressures

Divers using different cylinder sizes will find that calculating usable volumes is slightly more complicated, because they must ensure that each diver is allotted the same volume of gas. When divers have the same size cylinders, determining who has the most gas is simply a matter of checking fill pressures. The diver with the lowest pressure need only round their pressure down to a number evenly divisible by three, and then take one third of this value. This establishes the usable volume of gas for every team member. For example, a team with fills of 2,800psi (190bar) and 3,400psi (230bar) would establish its turn around pressure by first determining which fill is less, in this case the diver with 2,800psi. They would then round down the 2,800psi (190bar) fill pressure to 2,700psi (180bar) and take one third or 900psi (60bar) as their useable volume. Both divers would then subtract this volume from their fill pressure to determine their turn pressure.

11.6 Gas Management With Dissimilar Tanks

Dive teams frequently have tanks with different gas capacities. Although the use of different size cylinders requires a few calculations, the fundamental basis of team air management remains the same. Thirds calculations require that the team establish a maximum volume that can be used before the dive is turned. In overhead diving, such as cave, wreck, or ice, this volume is one third; the remaining two thirds is reserved for return and emergencies. Ocean dives that necessitate additional gas reserves require that divers initiate their ascent with at least one third of their starting volume still remaining.

There are a number of methods for calculating the turn pressure of each diver. One method that requires memorizing only one conversion multiplier is explained below. There are other methods more dependent on the use of conversion tables. Keep in mind that every calculation method becomes easier with practice, especially when the same team dives together often. Furthermore, bear in mind that divers relying on tables or charts will likely not have these available when they are most needed.

In order to calculate turn pressures for a dive team using dissimilar tanks, first determine which diver has the least amount of air. This is typically the diver with the smallest tanks. However, dissimilar fill pressures can result in a diver with larger tanks actually having a smaller volume of air. If members of the dive team are wearing different size cylinders, then calculating the available volume can be more complicated because equivalent pressures no longer indicate equal volumes. However, the goal still remains to prevent any one person from consuming more than the rest of the team, thus ensuring that each member has a sufficient reserve for emergencies.

11.6.1 Limit the Team's Penetration to One Third of the Smallest Available Volume

Dissimilar tank calculations rely on establishing a common volume that can be related to different tanks. For example, 3000psi (207bar) is not the same volume in different cylinders, making discussions about usable air in psi or bar nearly meaningless. Instead, divers must convert psi or bar to a universal value that can be related to various cylinders.

Thirds calculations with dissimilar tanks must be based on the diver with the lowest volume. This ensures that the diver with the least amount of gas has sufficient volume for an emergency exit. If team members are using different size cylinders, then divers must calculate this volume in cubic feet (or the metric equivalent, free liters) and apply it across cylinder sizes. Metric system conversions are substantially more simplified than cubic feet calculations. Examples of both can be seen below:

Imperial:

An 80ft^3 cylinder with a working pressure of 3000psi and an aluminum 50ft^3 with a working pressure of 3000psi will not contain the same volume of gas despite having equal fill pressures. If both tanks have a fill pressure of 3000psi they will contain 80ft^3 and 50ft^3 respectively. In order to calculate the available volume in cubic feet, one must divide the rated capacity by the **working pressure** (not the fill pressure).

For example:

The cubic feet/psi for an aluminum 80ft^3 cylinder with a working pressure of 3000psi is: 80ft^3/3000psi = .027ft^3 per psi.

The cubic feet/psi for an aluminum 50ft^3 cylinder with a working pressure of 3000psi is: 50ft^3/3000psi= .017 ft^3 per PSI

Therefore, respectively, at 1000psi the 80ft^3 would hold 27ft^3 (or .027ft^3/psi x 1000psi) while the 50ft^3 would hold 17ft^3 (or .017ft^3 x 1000psi). A diver with knowledge of their cylinder baseline could then be able to calculate the available volume at any fill pressure.

Looking back at the above two cylinders, one can now calculate their volume and determine which tank contains less. To calculate the total volume of the respective cylinders one only needs to multiply the cylinder baseline established above (ft^3/psi) the cylinder fill pressure.

For example:

The volume of gas, in cubic feet, of an 80ft^3 cylinder filled to 2100psi is .027ft^3/psi x 2100psi= 56.7ft^3

The volume of gas, in cubic feet, of an 50ft^3 cylinder filled to 3100psi is .017ft^3/psi x 3100psi= 52.7ft^3

The 50ft^3 cylinder still contains less gas and remains the volume that will determine the team's usable gas supply. Using the fill pressure of 3100psi one first rounds down to the evenly divisible 3000psi, and then divides by three (to get our one third); this leaves the team with 1000psi of available gas for penetration.

As we established earlier, however, 1000psi in a 50ft^3 cylinder is less in volume than 1000psi in an 80ft^3 cylinder. In order, then, to establish what volume of gas is available for penetration, one must first convert 1,000psi to ft^3. This comes out to be 17ft^3 (1,000psi x .017ft^3/psi). Now, if 17ft^3 represents each team member's available gas for penetration, then the next step is to convert this volume into psi, so that the diver with the 80ft^3 cylinder can monitor his/her consumption of 17ft^3 (in psi form) on his/her pressure gauge. Above it was established that an 80ft^3 cylinder's baseline is .027ft^3/psi (80ft^3 /3000). Now, if the diver with the 80ft^3 cylinder can only consume 17ft^3, then to determine what this volume translates into in psi, s/he will divide the available gas (in ft^3) by the cylinder baseline. This turns out to be 629psi (17ft^3/ .027ft/psi). After rounding down for conservatism (allows less gas for penetration) the diver in an 80ft^3 cylinder may only consume 600psi for penetration. This means that in order to consume the same volume of gas for penetration as the diver who is diving a 50ft^3 cylinder (whose turn pressure is 2,100psi), the diver in the 80ft^3 cylinder must turn at 1,500psi.

11.7 Battlefield Example for Dissimilar Tanks Conversion - Imperial System

Metric gas calculations are often easy to do in the water prior to a dive. Imperial measurements of volume, on the other hand, are cumbersome in the water. Thus, it is very useful for divers to understand, and be familiar with, the process of calculating cubic feet for different cylinders. Below are factors that will enable divers to quickly relate cylinders of different capacities.

Example: Two divers are going on a cave dive: one is using a set of $95ft^3$ cylinders filled to 3600psi, and the other is using a set of $121ft^3$ cylinders filled to 3000psi. What are their respective turn pressures?

TABLE 11.1 CYLINDER SIZE VS CUBIC FEET PER 100 PSI

Twin Tank Configurations (Divide by 2 for single)	GUE Factor = ft^3/100psi, rounded to nearest whole number (Tank size/rated pressure * 100 psi)
HP 80 (3500 psi)	5
HP 100 (3500 psi)	6
HP 120 (3500 psi)	7
LP 80 (2640 psi)	6
LP 95 (2640 psi)	7
LP 104 (2640 psi)	8
LP 121 (2640 psi)	9

Step 1. What is the volume in ft^3 for each of the cylinders?

Total Volume = GUE factor x (psi/100)

$95ft^3$ at 3600 = 7 x 36 = $252ft^3$ (cylinder contents)

$121ft^3$ at 3000 = 9 x 30 = $270ft^3$ (cylinder contents)

Step 2. Which has the least volume?

The diver with the $95ft^3$ cylinder has less gas, and defines the amount of gas that can be used on the dive and/or for penetration. Usable PSI = Total PSI/3.

Step 3. Calculate the one-third rule on smallest volume tank.

3600psi divided by 3 = 1200psi or $84ft^3$ (GUE conversion factor (7 x 12 = 84)). This represents the amount of gas that can be used for diving. Therefore, the turn pressure for the diver wearing twin 95's is 2400psi.

Step 4. Calculate the one-third rule for the 121ft^3 cylinders.

From step 3, usable ft^3 for this dive are 84ft^3, divided by the GUE factor for 121's (9), x 100 = Turnaround PSI = 84/9 x 100 = 933psi for penetration/diving. Rounded to 900psi for conservatism.

Step 5. Establish turn pressures.

95ft^3 cylinders: 3600psi – 1200psi = 2400 psi (turn pressure)

121ft^3 cylinders: 3000psi – 900psi = 2100 psi (turn pressure)

11.7.1 Metric Dissimilar Tanks Conversion Example

Example: Two divers are going on a cave dive: one is using a set of 12L cylinders filled to 180bar, and the other is using a set of 15L cylinders filled to 150bar. What are their respective turn pressures?

Step 1. What is the volume in free liters for each of the cylinders?

12L cylinder contains 2,160 free liters (12L x 180bar)

15L cylinder contains 2,225 free liters (15L x 150bar)

Step 2. Which has the least volume?

The diver with the 12L cylinder has less gas, and defines the amount of gas that can be used on the dive and/or for penetration.

Step 3. Calculate the one-third rule on smallest volume tank (12L)

180bar/3 = 60bar for penetration/diving, or 720free liters (12L x 60bar).

Step 4. Calculate the one-third rule for the 15L cylinders.

720free liters (from step 3) divided by 15L = 48bar for penetration/diving.

Chapter 12

Diving Procedures

12.0 Introduction

SCUBA diving has undergone a technical revolution in the last decade, allowing individuals to explore areas previously thought inaccessible to everyone except the world's most elite divers. This new access to what was historically inaccessible has occurred rapidly, and is raising questions about whether the many divers who are seeking to take advantage of this access are qualified to dive in these more challenging environments. To distinguish their pursuits from shallower, more "recreational" diving, divers who are exploring these new, demanding environments are typically referred to as "technical" divers. Generally speaking, technical diving has experienced a reasonable degree of success, allowing hundreds of individuals to explore progressively deeper and more complex environments.

Nonetheless, perhaps the single greatest challenge facing technical diving educators today is assessing whether technical diving is an appropriate pursuit for the active recreational diver. The "nearly anyone can dive" attitude, one which enjoys great popularity with the recreational diving market, not only fails to properly limit unqualified participants, but is generally inappropriate for technical diver training. This seems to be an emerging problem among the gatekeepers (agencies, dive shops, instructors, and individuals) of the technical diving industry, who fail to limit access, especially to the highest levels of technical diver training, to the unqualified. This has resulted in the following sad fact: technical diving fatalities are mounting, and the proficiency of the average diver continues to decline.

12.1 Accident Analysis

When compared to today's dives, many historically challenging dives are considered relatively simple. For example, in the past, 200-300ft dives were exceedingly uncommon. Today, given both helium-based mixtures and more refined diving techniques, diving has become much more ambitious. In a little more than a decade, technical diving has grown into an undeniable force in diving. Unfortunately, the hype associated with its advances have left many observers waiting, wondering, and debating.

Questions that concern observers are: "What are the risks of technical diving?" "What procedures are safest and which are most dangerous?" "What mixes, bottles, or regulators should one breathe?" "What equipment is most suitable for technical diving?" While many of these decisions are left up to the divers themselves, guided by varying "expert" opinions, the risks associated with technical diving remain largely definable. Or do they? The evaluation of cave diving risk began nearly two decades ago with Sheck Exley's Blueprint for Survival. To pretend (as we often do) that this data effectively describes modern day risk is questionable at best. Nonetheless, it remains likely that the same primary risk categories that Exley identified to be responsible for most cave diving fatalities (training, guideline, air supply, depth, and lights) are similar if not identical. Yet, there is some question regarding the completeness of this data, given the changes in the cave population, in the training regimens, and in technical divers in general.

To be sure, cave diving is a small subset of technical diving. Nonetheless, many advances have occurred in cave diving because, historically, cave divers have been more meticulous in their analyses of fatalities. Unfortunately, since Exley's attempt to delineate the causes of cave diving fatalities in his 1979 book, little has been done in either the cave or technical community to collect and describe diving risk. This lack of interest in accident analysis is embarrassing and potentially dangerous, because it is exactly this information that is often used to generate training curricula. Consider, for example, the role of accident analysis in the development of cave diver training.

Cave diving accident analysis is generally split into risks associated with the average (not cave) diver entering a cave, and those associated with cave divers entering a cave. Exley's primary risk factors included the following:

Lack of continuous guideline

Failure to reserve two thirds of gas supply for exit

Diving to excess depth

In 1984, training and lights were added to this list, both to highlight the risk associated with untrained divers entering caves, and to assert the need for sufficient lighting (which is primarily an issue of being untrained for cave diving). These two additions established the party-line criteria, which are taught in the following order:

Lack of cave training

Lack of continuous guideline

Failure to reserve two thirds of gas supply for exit

Diving to excess depth

Diving without sufficient lighting (i.e. at least one primary and two reserve lights)

However, for trained cave divers, the proposed risk factors are not only more restricted, they are also ordered differently:

Diving to excessive depth

Lack of a continuous guideline

Failure to reserve two thirds of gas supply for exit

The above categories create the illusion of well-defined risk. Though these categories are good at establishing primary risk factors, they are far from exhaustive. Whatever the degree of statistical precision associated with the original analysis, it is nonetheless heavily distorted by a number of factors, including changes in diving popularity, advances in technology, and effectiveness in the education of risk factors. Consider, for example, the not too distant past when cave divers could claim not a single fatality among properly trained cave divers. Now compare this to the nearly regular stream of certified cave fatalities today. What accounts for this changing landscape?

Even though factors like the huge increase in the cave population skew these numbers, nonetheless, this increase does not account for the above phenomenon, especially when one reviews the details of these fatalities. What seems to be at the core of the problem is that cave training appears to have lost its original rigor and care. Actually, this is a small part of a larger problem, in that there is a general decline in the quality of diver training. Many divers have noticed the general decline of diving ability in the dive community, stretching from open water instructors with weak skills to poorly trained students. The demanding nature of technical diving makes this loosening of standards, and the resultant decline in diver skill, particularly problematic.

Technological advances have also served to call into question the exhaustiveness and/or accuracy of the original risk assessment. According to the above, deep diving is the greatest cause of death among certified cave divers, and therefore, by extension, the greatest source of risk. However, relatively few cave diving fatalities have occurred when sensible helium-based gas mixtures where used; meaning that, unless one examines the role of air diving in deep cave diving fatalities, to assess risk on the basis of the traditional model would be suspect, at best.

To be sure, deep diving has its own distinct set of risks, e.g. increased time pressure, more rapid gas consumption, and those risks related to decompression. However, to promote the view that deep diving itself is responsible for most of these fatalities prevents divers from grasping the true risk associated with deep air diving. Understanding the role of air diving in deep cave diving fatalities would most likely have impacted the history of deep air diving, and softened the strange resistance the community has to sensible breathing mixtures.

Further eroding our ability to make educated choices on the basis of this traditional assessment of risk is the fact that these risk factors are no longer tracked with any degree of statistical precision. For example, some diving leaders have proposed adding solo diving to the list of risk factors. While solo diving has certain risks, and is generally not recommended, the arbitrary addition of another risk category can distort the accuracy of risk determinations.

Nonetheless, current cave diving risk factors undoubtedly provide divers with good general information, and for that reason can be highly instructive. However, divers should be aware that these traditional categories have a certain degree of prejudice built into them, and, before acting, should factor this into their deliberations.

12.2 Relating Cave Fatalities To Technical Diving

The preceding section discusses cave diving risk factors not only because, despite their limitations, they are undoubtedly central components of what objective risk there is in cave diving, but also because they relevant to all technical diving. Exceeding one's limitations, physical or psychological, is often a significant contributor, if not the cause, of most fatalities.

The following list outlines common risk factors associated with diving accidents:

Exceeding one's level of training

Going beyond one's personal level of comfort/ability

Diving beyond the range of one's gas mixture

Using improper or insufficient equipment

12.2.1 Exceeding One's Level of Training

Divers that try to cave dive without training place themselves at significant risk, regardless of their personal ability and diving experience. Individuals that are proficient in one area of diving are often ill-prepared for the inherent dangers of an unfamiliar one. One of the most valuable aspects of diver training is helping individuals to properly identify and manage the risks associated with a certain type of diving. Proper training does not insulate one against risk, but it can outline areas of particular concern and prepare individuals to manage these with proper techniques and sensible diving practices.

12.2.2 Going Beyond One's Personal Level of Comfort

Training is a central component of diving safety, but without common sense and honest personal assessment, it can be nearly meaningless. Far too many divers view a certification card as insurance against risk, when it is only a license to learn outside the guidance of an instructor. During proper training, divers should gain an appreciation for the risk and management of common problems. However, the burden still falls on certified divers to be sensible about the inherent risks of a particular dive, choosing not to partake in one if it stands to tax their level of comfort and personal ability. Proper training is responsible for providing divers with an appreciation of the true risk of a given activity; it is the responsibility of the certified diver to use that information to evaluate his/her preparedness for a particular dive.

12.2.3 Diving Beyond the Range of One's Gas Mixture

Technical divers regularly lose their lives by breathing an inappropriate mixture. As a result, there has been a great deal of attention focused on why divers accidentally breathe the wrong decompression mixture at depth (i.e. accidentally breathing oxygen instead of Nitrox), and, as a result, convulse and drown. These errors nearly always seem related to poor tank marking and to ineffective gas switching procedures.[1] However, divers also often make foolish decisions regarding what kind of mix they will use for a given exposure. For example, divers routinely dive deeper than 100ft (30m) on air (a known narcotic gas) and on excessively high PO_2 (greater than 1.4 while working), thereby exposing themselves and their team members to risks that should not reasonably exist. Divers are typically free to make their own choices about breathing mixtures, however, because of the unnecessary level of risk involved, choosing to dive gasses that exceed 1.4 PO_2 and 100ft END demonstrates lack of sound judgment and great irresponsibility.

12.2.4 Using Improper or Insufficient Equipment

The most obvious case of improper equipment use involves individuals diving in an environment without the necessary safety equipment. Examples include divers entering overhead environments like wrecks or caves without guidelines, ice divers not using surface lines, divers drifting without surface markers, deep divers using substandard regulators, and divers entering caves without sufficient lighting. Countless fatalities point to the need for proper equipment; divers who ignore this place themselves at much greater risk. Technical diving is not an activity that permits equipment to be safely cobbled together from odd pieces. Proper technical diving requires divers to make an investment in their safety, and not accept substandard equipment or allow themselves to be lured into environments without the right tools for the task at hand.

Technical diving is as much about having the right attitude as it is about carrying the right equipment. To have one without the other would lead one into dangerous waters. There are many subtle encouragements to follow questionable diving practices; the apparent success of these practices can lull divers into a false sense of security. Furthermore, divers are resistant to changing commonly accepted practices, regardless of their actual track record. Divers that wish to maximize their fun and safety while enabling maximum performance

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1 Please refer to Chapter 6–The Logistics of Diving Mixtures Other than Air.

must carefully choose their mentors and their dive buddies. Common sense practices are sometimes anything but common.

12.3 Stress on the Diver

No discussion of accident analysis would be complete without addressing the role of stress in accidents and fatalities. Stress, here, refers to factors that evoke both a physical and a psychological response. Many activities result in an accumulation of stress. Its presence often performs the invaluable service of alerting individuals to approaching limitations. In diving, as in life, one's goal should not be to eliminate all forms of stress, but to maintain control over it, and to read its message. In truth, many fatalities have resulted from improperly managing fairly simple mistakes. These errors can accumulate, to the point where they overwhelm the diver.

Consider, for example, a diver that is improperly weighted, with poor trim and/or buoyancy. As this diver overexerts him/herself and accumulates CO_2, his/her stress levels rise. Should the diver or one of his/her buddies note this problem, the team could be notified, the problem rectified, and/or the dive terminated. Alternatively, divers have and will be pushed into psychologically and physiology outpacing their comfort, leading to panic and death.

12.3.1 Recognizing Stress

The initial stages of stress often evoke minor changes. An individual may begin to breathe more rapidly and may find it difficult to remain cognizant of the surroundings. Additionally, the stressed diver often experiences a narrowing of perceptions and develops increased clumsiness. An elevated breathing rate is often accompanied by shallow breathing, which does not properly vent the lungs and leads to carbon dioxide retention. CO_2 retention can itself lead to higher levels of stress, as excess levels of carbon dioxide stimulate a respiratory response that creates a feeling of urgency. As the diver attempts to replenish the needed oxygen, the result is often rapid, shallow breathing. This poor lung ventilation may lead to even higher levels of carbon dioxide in the bloodstream, perhaps further increasing one's stress level in a dangerous feedback cycle. When experiencing stress, a diver should stop, breathe slowly and deeply for several cycles, then evaluate the situation. Often all that is required is time to catch one's breath, but it is important not to let stress get out of control.

When a diver feels that the stress level is mounting, s/he should stop and breathe deeply, venting the lungs of excess carbon dioxide and introducing much needed oxygen. While rapid, uncontrolled breathing is a common reaction to stress, other relatively obvious signs may also be present. Divers who find it difficult to remain aware of their surroundings are frequently said to be experiencing tunnel vision. These divers focus on one particular object to the exclusion of their surroundings. This lack of attention may result in any number of negative consequences, i.e. lost line, lost dive buddy, violation of proper air rules, and/or poor fin technique. Most divers become clumsy in the presence of stress. A clumsy individual is more likely to become entangled in the line or crash to the floor, perhaps disturbing the sediments. Divers who experience reduced control are likely to hit obstructions, damaging the environment, their equipment, and themselves.

12.3.2 Coping with Stress

The best way to manage stress is to remain alert and anticipate its development. One should not seek to force oneself through overtly stressful situations. Instead, high levels of stress indicate the need for the team to stop and regain focus. Do not be afraid to stop, or to force an errant buddy to stop and gain control.

Many fatalities are the sequential combination of several poorly managed problems. Individuals frequently make poor decisions in stressful situations. By increasing one's fitness level, and by remaining committed to halting dives that have the potential of mushrooming out of control, divers have the ability to control their stress and manage situations effectively. Each diver is responsible not only for monitoring his/her own stress level, but for remaining aware of signs that team members are not comfortable.

12.3.3 Panic

When the stress level climbs out of control it leads divers into panic. In a panic-stricken state, individuals are unable to think rationally; fear takes control. Most panic-stricken divers try to grasp others and/or swim immediately to the surface. Irrational ascents to the surface are very dangerous in all situations, particularly in overhead conditions or when there are decompression obligations. If stress becomes a problem, divers should stop and focus on slow, deep breathing, taking time to bring down escalating levels of stress.

Stress levels can be controlled with relative ease. Most divers find that a few dives into a new environment are all that is needed to increase their comfort level. If a diver feels inordinately stressed while diving, s/he should terminate the dive, and evaluate whether diving is a suitable activity for him/her. The world is replete with exciting and fascinating activities. If diving in general, or a particular kind of diving, is not fun for an individual, then it should be forsaken for another activity, regardless of desire or peer pressure. Heavy stress undermines what should be a pleasant activity, while uncontrolled stress results in panic, which is rarely a survivable event.

12.4 Team Diving

Team diving is an important part of any type of diving. Nonetheless, to assert the value of team diving does not detract from the need for individual competence. On the contrary, team members should all be individually capable of any given dive, thereby increasing the safety of the team as a whole. Divers that are less capable can bring the team to a lower level of proficiency and compromise the team's safety. Dive plans should cater to the weakest diver, leaving teams to choose their members carefully, particularly as the dives become more aggressive.

Buddy separation is almost always due to careless diving. In recreational diving, individuals are instructed to search for one minute and then surface. However, in most forms of technical diving (deep, decompression, overhead), this is not feasible; therefore, divers must use extra care to avoid separation. Astute divers will rarely, if ever, become separated from a dive buddy. By remaining aware during the dive, and frequently checking each other's location, buddy teams can easily stay together. In this regard, powerful underwater lights facilitate team coherence and communication. Even in the open ocean, lights that are 30 watts or greater promote excellent communication between team members and provide dive buddies with excellent visual references. Divers can move through the water regularly referencing one another, and by passing the light across their buddy's visual field (not in the face) provide a constant source of reference. Divers that make it easy for others to stay with them will enjoy much greater team support and comfort.

It is possible to dive alone, but team diving with a qualified dive buddy increases safety and is far more rewarding. Dive teams can relay important information about individual diving technique to each other, point out features that others may miss, prevent troubles before they occur, and assist in emergency situations. Individuals that view team diving in a negative light have never enjoyed the benefit of a good dive buddy.

12.5 Cave Diving

Cave diving is a very specialized form of technical diving. Like many types of specialty diving the elements of safe cave diving are relatively straightforward, but not necessarily intuitive. As such, all divers, regardless of proficiency, should seek cave diver training to safely access the interior of a cave. Cave diver training is usually composed of several different courses, each building upon the training of the previous course.

Caves vary from large open areas flooded by daylight (usually called caverns), to very extensive passages that can extend miles from the surface. The current world cave diving penetration record is nearly four miles long, at a depth of 300ft (90m), and is held by GUE President Jarrod Jablonski and WKPP Director George Irvine. Some cave diving involves partially dry areas (called sumps); other cave diving involves lava tubes from volcanic action. Caves are remarkable places; they are mysterious and beautiful. But exploring them is not for everyone. Proficient divers with good basic diving skills should think about introductory training after considering what is required.

Divers seeking cave training should progress methodically through their training, and ignore any encouragement there may be to progress rapidly to upper levels of cave certification. Cave training is widely recognized as the best type of education that divers can receive with respect to skill building, awareness, and teamwork. However, like most valuable skills, cave diving proficiency takes time and effort; individuals that are interested in cave diving should emphasize the process, not the end of certification. This manual is not intended as a cave diving resource, even though it overlaps at times with what one will find in cave diver training manuals. Divers interested in cave diving should consult GUE's Cave Diving Manual as well as visit www.gue.com to read about their suitability for cave training.

12.6 Cold Water

Some divers do not consider cold water diving to be an unusual activity; however, diving in cold water creates additional stress and difficulty. Divers that are properly outfitted in good thermal protection are able to dive efficiently in areas that are near freezing. With the exception of good thermal protection, the equipment utilized in cold water diving is nearly identical to that of other properly configured technical divers. Diving in cold water is undoubtedly more difficult and dangerous than similar dives in warm water, however, with a good set of basic skills, most divers will be able to adapt to this hostile environment.

Cold water diving presents its own array of problems, i.e. reduced decompression efficiency, potential for thermal failures (e.g. dry suits) and the associated dangers, and reduced manual dexterity from the numbing cold, particularly as the dive progresses. To some extent, regardless of whether they are consciously aware of it or not, cold water divers experience a degree of stress associated with immersion. Furthermore, diving in cold water also greatly increases the risks associated with being separated from the diving vessel, as divers can quickly develop critical hypothermia. Electric suits may allow divers more comfort in very cold water, but relying on these systems can be very problematic in the event of a failure.

Other equipment failures include regulator, dry suit inflator, or BC inflator freezes. In very cold environments, clips and zippers may also freeze on the surface, where temperatures can plunge well below freezing, another reason to ensure all clips can be cut free, i.e. no metal-to-metal connections. Simply spitting in one's mask can create freezing problems, as can breathing a regulator at the surface. Breathing regulators at the surface can introduce humidity, which can promote freezing.

12.6.1 Ice Diving

Ice diving is obviously a subset of cold-water diving, and requires good cold-water skills, as well as the ability to manage overhead diving. Cave diver training is often not required for this form of diving, but could be extremely beneficial in this regard, particularly if one's exposures surpass recreational ones. Individuals interested in ice diving should seek training and get experience with local ice divers. Several ice diving groups have approached ice diving carelessly and lost their lives. Beyond ensuring that the ice sheet is stable and thick enough to support the diving crew, individuals should make certain that all divers are tethered to the surface, with support divers prepared to assist.

12.7 Wreck Diving

Wreck diving does not enjoy a widely recognized form of standardized training, and different individuals view wreck diving differently. Some divers will only circle the exterior of a wreck without ever venturing into the superstructure. Others will venture deep into the superstructure, examining its contents or searching for artifacts. Several instructors offer wreck training; also, some organizations offer courses in wreck diving, which are in large part orientation classes, lacking in overhead and advanced training principles.

Wreck penetration can also vary from superficial forays into the structure to detailed reconnaissance missions deep into the superstructure. Most avid wreck divers pursue and recommend cave diver training, and then adapt that training to wreck penetration. While cave training is very effective at preparing one for any general overhead, individuals must recognize that the wreck environment has many notable dangers that do not exist in cave diving.

In many ways, wreck diving is inherently more dangerous than cave diving. Wreck dives are more sensitive to changes in weather and the resulting water conditions. Furthermore, wrecks are constantly in the process of degrading, and are rife with decaying structures, entanglements, sharp edges, and marine life. Wrecks often have multiple entrances; confusion is frequently compounded by light streaming in from portholes and other false exits. Lastly, complications may prevent a wreck diver from returning to the dive boat. For example, divers could become lost at sea or succumb to frigid waters.

12.8 Diving From a Boat

Boat diving procedures can vary noticeably from one region to another. This is because some areas are consistently cursed with rough seas and heavy current, whereas others are blessed with continually flat seas and no current. Typically, conditions lie somewhere in between. The most important consideration here is to properly identify the risks and strive to eliminate or reduce them. For example, regardless of conditions, divers should strive not to be lost by the dive boat. When diving deep in high current and cold water, separation from the support vessel is more likely and more dangerous. Regardless of the situation, steps must be taken to ensure that both the team and the boat can be reunited at the end of the dive, and that emergencies will not leave the diving team stranded.

12.9 Anchor Diving

When conditions are good (moderate to low seas and light current) boats may choose to anchor in a particular spot, while divers explore the nearby vicinity, usually heading into the current in the first part of the dive. At a predetermined point, usually based on time and/or available air supply, the dive is "called", and the divers return to the boat. Obviously, anchor diving requires that divers are able to swim against whatever current is present, and that the seas are sufficiently low so as not to produce unsafe boat conditions. An anchored boat will be abused by high seas and will not be able to remain tethered in very rough conditions. Anchor diving must be done with a fixed diving location so that the dive team can stay near the boat.

12.10 Drift Diving With a Surface Marker

If sea conditions consist of strong currents and/or moderate to rough seas, dive operators will often (if conditions are safe) have the dive team drift with a float ball or other obvious surface marker. The dive boat will then float near the ball, providing support and/or notifying vessels in the area that divers are below. Divers drifting in the open ocean must have a surface marker so that the boat can remain with them. Surface currents can easily vary from currents at depth, making it impossible for the boat operator to identify where the team is located without a surface marker.

Heavy surface currents can pull the diver's float. When this occurs, a thin line to a dive flag on the surface can greatly reduce management difficulties. Drift diving with a surface marker is problematic with multiple teams and/or bad weather, such as high seas or fog, as the boat may have trouble locating or maintaining contact with the dive team. Such conditions require multiple boats or a single team. If there is any doubt regarding whether or not the boat can track the team, a new plan should be devised, or the dive terminated.

12.11 Drifting into a Fixed Point

Occasionally, experienced technical divers will dive a location by drifting into a fixed point (like a wreck), exploring the location, and terminating the dive at a fixed time/gas supply. The team can then shoot a lift bag or other surface marker to notify the boat operator of a now-changing position. The boat would stay above the coordinates of the location until seeing the surface marker and then drift with the team. This system is most commonly used when conditions such as a strong current make it impractical to "hook" the location with a surface marker or an up-line.

If the team is unsuccessful in locating their objective, they should terminate the dive and deploy a marker buoy/surface float so that the boat can follow the team's position. Without a fixed diving location, or a surface marker, it can be very difficult for a boat to maintain contact with a dive team. Separation from the diving boat can be extremely dangerous, as teams in ocean currents may drift for miles. Separation from the dive boat can result in divers becoming lost at sea and/or cut off from the emergency support of a diving vessel. Unfortunately, it is not uncommon for subsurface currents to vary from surface currents, greatly increasing the risk of diver separation. Divers drifting into a fixed point can suffer the same difficulties as discussed above. Diving with multiple teams must be managed accordingly.

12.12 Getting Back to the Boat

Divers have a variety of ways of exploring a diving location; however, all boat diving requires that divers be able to return to their diving vessel. In some situations, it is imperative that divers be able to locate the dive boat, in others (such as near shore), it is less so; nonetheless, divers should never get careless about locating the dive boat, as it can be very difficult to find lost divers at sea, particularly in poor weather or low light conditions. In heavy currents or cold water, it becomes even more essential for divers to remain close to the diving vessel or to its chase boat.

Anchor diving is only done in limited or no current, making significant separation from the diving boat extremely unlikely. With drift divers, the use of a surface marker makes it relatively simple for the boat operator to maintain contact with them. Problems returning to the diving boat are most likely the result of diving a fixed point such as a wreck in heavy currents, or of drift diving when bad weather sets upon the dive team.

Divers that drift into a location, or follow the anchor line to the wreck, must find their way back to the diving boat in one of several ways. If the diving boat is hooked to the wreck, the team will make its way back to the boat by ascending a fixed line (also called the up-line). If the diving boat is not anchored, then they will commonly drift from the wreck and deploy a surface marker to allow the boat to stay with them. Another case where teams will drift and deploy a surface marker is when dive teams are unable to return to the up-line due to high currents, misdirection, or emergencies.

12.13 Inability to Return to the Up-line

In some areas, divers prefer to "hook" the wreck and use the anchor line for descent and ascent. However, if the team is unable to reach the up-line because of misdirection or an emergency, they must either drift from the wreck and deploy a surface marker, or attempt to fix a deployed marker to the wreck and ascend along this line. In moderate current, divers will not drift far from the diving spot, making distant separation unlikely. However, in high currents, divers drifting from the wreck could become substantially separated from the surface vessel. Even so, trying to ascend a line fixed to the wreck in heavy current leaves the team exposed. It is generally preferable in these situations to drift from the wreck, deploy a surface marker, and allow the surface and/or chase boats to track the dive team.

Deploying a surface marker while drifting can be problematic should divers be in an area where very poor surface visibility (such as high waves and/or heavy fog) makes it difficult to locate them. This situation may be compounded by dives where multiple teams are on a wreck, and an insufficient number of support vessels prevents each team from being followed. In such areas, divers may prefer to fix a line to the wreck and ascend along it, staying near the surface boat and limiting the risk of separation.

12.14 Surface Support

Lastly, it is important to note that adequate surface support is critical to ensuring diver safety. Without adequate support, surface floats and/or deployed lift bags are difficult for a captain to spot and follow. The degree of support necessary depends on the particular dive being undertaken. For example, anchor diving in warm, shallow water with no current requires limited support. On the other hand, decompression dives in cold water with high currents requires more robust support. Support divers can dive down an up-line and provide assistance (i.e. additional gas), and assist the captain in maintaining a fix on surface markers. Support is particularly beneficial when divers engage in decompression diving, as the potential for problems increases with the addition of diving variables.

Where possible, it is beneficial that surface support have medical training, as they may provide life-saving assistance during the initial phase of an emergency. Furthermore, support personnel must have access to some form of communication to arrange for emergency assistance. The type of communication and surface support needed varies with each situation/environment. For example, boats may use either a combination of maritime communication or cellular phones to establish proper emergency communication. Divers participating in land-based activities, such as dives in a lake or cave, might use a cellular phone or CB radio.

To maximize safety and efficiency, decompression dives that are done in areas with high currents require chase boats and support diving personnel. A chase boat allows the primary dive vessel to remain fixed to the diving spot, while the chase boat splits away and drifts with divers that were forced to abort the up-line ascent. Ideally, each diving team would have a dedicated chase boat that could function as their support in the event that all teams were separated from the wreck and drifting in the ocean.

Regardless of the environment, teams must formulate a plan that, minimally, addresses the following contingencies.

Diver is separated from surface support, or has not returned at prearranged time

Search procedure

Notes indicating time, depth, current etc., taken for rescue personnel

Injured diver in need of medical care and transportation

Proper contact information

Determine most efficient transportation (i.e. land, sea, air)

Proper procedure for the management of decompression sickness or other injuries

First aid for DCS or injury

Recompression when no other viable options exist

Procedure for injured diver while other divers remain in the water

Do not strand other teams

Transportation for injured diver

Procedure for managing sudden change in diving conditions (most notably bad weather/ currents)

Procedure for managing the damage or loss of support vessel

12.15 Proper Diving Technique

Poor diving technique can greatly increase diver stress and reduce the ability to manage emergency situations. Most emergency situations are the cumulative effects of a series of smaller, manageable problems, and often involve poor diving technique and/or awareness. Divers with good buoyancy and trim are far less prone to unnecessary stress, and much better prepared to manage diving problems.

The words trim and buoyancy have commonly been used interchangeably. Though they are related, trim and buoyancy are two different elements of efficient diving, each requiring practice to master. Once they are balanced, divers will discover that their swimming effort and gas consumption will decrease, making dives longer and easier. Good buoyancy control is important to any form of diving, but particularly to cave diving. Just as important, if not more so, is a diver's trim. Trim is the actual position in which a diver hovers and swims. While good buoyancy control usually conveys a diver's level of experience in the water, proper trim marks mastery of efficiency. Good trim requires that a diver moves through the water in a horizontal position with his/her feet up. Most divers swim with their feet in a down position, using a kick that gives downward thrust. This increases their surface area and the energy necessary to propel them forward. It is also crucial to realize that the feet down position will lead to injured coral, bad visibility, and damaged cave, all of which should be important concerns for divers.

Proper trim can be negatively impacted by several factors, one of which is BC design. BC's with restrictive bungee can promote gas trapping, and increase drag by generating turbulent flow around the diver. Trapped gas pockets can imbalance the diver with unequal pockets of lift. Furthermore, traditional jacket-style buoyancy compensators generally lift the upper portion of the body, making it even more difficult to remain horizontal. Practiced divers may be able to overcome this shortcoming, but back-mounted buoyancy compensators facilitate proper trim.

Proper trim can also be impacted by conventional open water weighting systems which position the bulk of a diver's weight around the waist. Technical divers usually avoid this by using double tanks. Nonetheless, both recreational and technical divers can benefit from redistributing this weight. For example, instead of wearing lead around the waist, a diver can use a stainless steel back plate and/or place weight underneath the back plate (such as a v-weight for doubles), or use a keel weight on the back of a single tank when diving singles.

Steel tanks can also be used to limit the need for additional weight. However, divers must be careful not to overweight themselves; they should evaluate their buoyancy to ensure that they are properly weighted. Divers should be able to hold their position in the water at 10 feet (for safety/decompression purposes) with nearly empty tanks. Divers who are underweighted could float to the surface should an equipment failure cause a loss of gas supply. Alternatively, a diver that is over-weighted requires more air in the BC, thereby increasing drag and the energy required for forward propulsion. The stress of struggling against improper weighting can, in and of itself, create enough stress to initiate an emergency.

Over-weighting can also leave a diver in serious trouble should s/he suffer a BC failure. Unfortunately, instead of focusing on proper weighting, many instructors and divers focus on large BC's and on redundancy. In certain situations, heavy steel tanks are justified by the need for additional air reserves, or by the need to offset positive buoyancy in the case of dry suit diving. If specific dives require equipment that overweights the diver in deep or bottomless environments (deep ocean or cave), the diver should maintain redundant buoyancy (e.g. a dry suit). Divers should adjust their equipment to allow them to swim to the surface in the event of an equipment failure.

Historically, recreational divers have carried all their additional weight on a weight belt, and have been taught to drop all of that weight in the event of an emergency. With divers wearing substantial amounts of weight when diving with a dry suit or thick wet suit, this process can be dangerous. Divers dropping 20 or 30 pounds could become substantially positive, resulting in an emergency situation now compounded by a buoyant ascent.

It is difficult to overemphasize the importance of proper weighting, good buoyancy control, and efficient trim. In extreme cases, failure to properly manage these has led to senseless tragedy. For this reason, divers should constantly strive to improve in these areas, by paying careful attention to their own performance, asking others for critical advice, and having their in-water performance videotaped by another diver.

Chapter 13

Emergency Procedures for Unconscious Divers

13.0 Introduction

As with most life threatening situations, the proper management of an unconscious diver relies on a speedy response, good choices, and luck. Numerous remarkable stories pay tribute to the possibility of rescuing an unconscious diver. In cold water (less than 70°F/20°C), divers have been revived after as much as 70 minutes of immersion. The resuscitation of victims after long immersions is more the exception than the rule, but is a testament to the possibilities inherent in emergency situations.

13.1 Unconscious Diver At the Surface

The diver should be stabilized with his/her mouth out of the water. This is generally done by floating the diver on his/her back and stabilizing the head. An airway should be established, and breathing, pulse, and general condition ascertained. If a boat is available, it is preferable that it come to the victim and rescuer. If it is necessary for the rescuer to swim to the shore/support vessel, great care should be taken to ensure that the victim's airway is maintained, and that water is kept from entering the mouth. Some individuals prefer to use mouth-to-nose breathing for in-water resuscitation. Divers must evaluate their ability to keep water out of the airway in this and, in fact, all water rescue techniques.

If the victim is not breathing, then the rescuer must breathe for the victim. CPR is not feasible in the water. If the victim is without a pulse, the rescuer should breathe for the victim and make haste to reach an area where CPR is possible. Breathing is commonly done mouth-to-mouth while pinching the nose, or by holding the mouth shut while breathing mouth-to-nose. Breathing cycles follow commonly accepted ventilation procedures (all divers should have CPR/First Aid training). If surface conditions are favorable (very little wave action), then it is preferable to remove the victim's mask to ensure both a good mouth-to-mouth seal and a proper nose pinch. In rougher seas, it may be beneficial to keep the mask on the victim's face to protect the airway.

Breathing for the victim can also take the form of positive pressure from a scuba regulator. Gas delivered from a scuba regulator may deliver a noticeably higher percentage of oxygen to the victim (as in the case of Nitrox). Furthermore, in rough surface conditions, divers can protect the airway and limit the risk of introducing water in the breathing passage by using a regulator to deliver gas to the victim. However, one must be aware that excess air delivered via the regulator can create a lung expansion injury.

13.2 Unconscious Diver At Depth

An unconscious diver at depth calls for a particularly speedy response on the part of the rescuer. Common wisdom recommends leaving the victim's regulator exactly where it is found. For example, if the regulator is out of the victim's mouth when s/he is found, it has historically been recommended that it be left like that. If an unconscious diver has lost the regulator from the mouth, the airway may be filled with water. The rescuer should recognize that, in such a case, the only definitive treatment is to bring the diver to the surface, and should make every effort to do so as soon as possible. In the event that decompression or overhead restrictions do not preclude a direct ascent, the rescuer should get a firm hold on the victim and bring him/her to the surface.

Holding the victim can be done by running the right hand under the victim's right shoulder and, by placing pressure on the chin, holding the regulator in the mouth. The rescuer can then use his/her left hand to control buoyancy, dumping air as required. In any case, the rescuer should prioritize getting the victim to the surface by a controlled ascent. Upon reaching the surface, the rescuer should treat the victim as an unconscious victim as described above.

In the event that it is not feasible (i.e. overhead environment or decompression obligation) to take the victim directly to the surface, the rescuer must evaluate several options. If the victim and rescuer are both under a significant decompression obligation, the rescuer must decide where the risk is highest. If surface support is available, it is generally best to deliver the victim to surface support, and return to decompression. The rescuer should return to decompression rapidly (three minutes or less), because his/her risk of DCS greatly increases with time at the surface. In this scenario, although the victim and possibly the rescuer may suffer DCS, DCS is treatable. Death by drowning is not.

Should the decompression obligation be significant, or overhead conditions preclude bringing the victim to the surface, the rescuer has little choice but to attempt in-water ventilation. Such ventilation is possible with a scuba regulator. If successful, this could return the victim to a conscious state, where they could carry out proper decompression. If the victim is separated from the surface by an overhead (such as in a cave or wreck), it may be possible to invert the victim (head down) and vent the water from the breathing passage. Again, the goal would be to safely remove the victim from the overhead region while preventing significant water from entering the lungs. If the victim is a significant amount of time away from definitive rescue from the surface, it is worthwhile to attempt in-water regulator ventilation. The effectiveness of such rescue is unknown, and heroic efforts are not likely to succeed; nonetheless, they provide the victim with some chance for survival.

In many cases, unconscious divers can be brought to the surface. When the surface is a viable option, it is best to bring an unconscious diver to the surface.

13.3 Reasons for Losing Consciousness

Divers may lose consciousness underwater for a variety of reasons, including:

> *Hypoxia* or *CO poisoning*: Using the victim's breathing gas would be unwise if this problem is suspected. Rescuers should use only a known breathable source.
>
> *Seizure*: This is a survivable event in some cases. Transient apnea is common after a seizure, but should only last seconds to a minute or two. In an air environment, death from an oxygen seizure is extremely unlikely. However, underwater, it would be necessary to protect and maintain the airway, and possibly ventilate the victim for a short period of time. Again, use of an alternate gas mix to ventilate the victim may be beneficial. Another consideration here is that when the diver awakens from an oxygen seizure, s/he will not be cooperative, but very disoriented and most likely extremely difficult to manage.

Narcosis: Historically, this is related with a breathing but "unresponsive" diver. Maintaining an airway and ascending to shallower water may restore cognition. However, the most sensible alternative is to avoid narcosis with responsible gas mixes.

Out-of-gas drowning: It is likely difficult to resuscitate a victim in this category, but with time and no other reasonable options, ventilation attempts are worthwhile. This is especially true in cold water, where miraculous saves have been made.