

The world's first and smallest aquanaut and underwater habitat. From Bail, Th., 1907, Beobachtungen über das Leben der Wasserspinne (Argyroneta aquatica), *Naturw. Wochschr.* 22:627.) See page *x* for explanation.

Living and Working in the Sea

James W. Miller

Ian G. Koblick

SECOND EDITION

Illustrated by
William Boggess



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Dedication

In appreciation for their assistance and perseverance, this book is dedicated to our wives, Ardeth and Tonya, who through the years have supported and aided our efforts to enhance human capability to live and work in the sea. They have waited patiently on the surface while we carried out experimental programs on the seafloor and have offered encouragement continually throughout the preparation of this book.

Acknowledgments

We thank the following persons who have influenced and helped us to develop and implement the habitat programs in which we have been involved. Some have provided support resulting in the implementation of major undersea programs, and others provided the long, hard hours day after day that kept these programs running safely and smoothly. These individuals are Edward Gieger, Jr., Frank Milhoan, Neil T. Monney, H. A. O'Neal, Denzil C. Pauli, and John H. Perry, Jr.

Appreciation is expressed to Lee H. Boylan for his valuable assistance in the compilation of information on European habitats he gathered and cataloged over the years. Thanks also are offered to Betty Estes who conscientiously typed the entire manuscript.

In particular, our gratitude and appreciation are extended to William Boggess, who not only illustrated this book but who reviewed and edited each chapter in the early stages of preparation.

Explanation of Frontispiece

The Frontispiece shows the remarkable water spider *Argyroneta Aquatica.* Found in the lakes and ponds of the temperate regions of Europe and Asia, *Argyroneta* spends its life underwater in and around a thimble-shaped diving bell constructed of carefully woven silk suspended among water plants. This unique spider, ranging in size from 0.35 to 1.1 inches, supplies itself with air periodically by swimming to the surface, capturing an air bubble, and maneuvering so that the body becomes cloaked in air. Although living underwater, the body must be kept dry at all times which is achieved probably through the emission of a waterproofing fluid, a kind of wet suit. When encapsulated with air, *Argyroneta* dives to her underwater habitat and releases the bubble inside allowing her to remain there for hours before returning to the surface for another air bubble, the time dependent upon the amount of activity and oxygen content of the water. As winter approaches, *Argyroneta* builds a stronger habitat that is sealed with silk and converted into a closed cell. Sometimes snail shells are used by males who line them with silk, fill them with air, and seal themselves in. While in a state of hibernation, this amazing animal can survive on a single large bubble of air for as long as three to four months, clearly establishing itself as the world's record-holding aquanaut. (Data from Bristowe, W.S., 1958, *The World of Spiders,* Collins, St. James Place, London.)

Foreword

To most natural scientists, Earth is known as the water planet, since no other in our system shows certain evidence of that apparently simple yet incredibly complex compound. Surely life as we know it cannot exist in its absence.

The full history of human dependence on oceanic, lake, and riverine environments has not yet been told, though most of us are vaguely aware of major elements of the story. It is generally appreciated that all civilizations, present and past, have depended on some manner of water transport for development, expansion, or simple survival. First, rivers were crossed and colonized throughout their navigable lengths; next, inland seas were exploited as relatively safe areas of commercial transport and colonization. Finally, the oceans yielded to the great pressure for exploration, expansion of populations, and commerce between continents.

The availability of our global waters promised more, however, than a mere buoyant interface for mercantile transport. In time, humans found it desirable—even necessary—to inject themselves into the undersea environment. Practical experience soon demonstrated that severe constraints were imposed by physiological limits of both depth and time of submerged exposure. For these reasons, until only two decades ago, the diver's limit for all practical purposes was a depth of 200 feet for a period of only 30 minutes. This boundary was broken with the development of saturation diving techniques.

The thrust of this book is to clarify the certain need for humans to make personal penetration into the ocean waters, where they can act as free agents for long periods of time. In this capacity, the human diver acts as the single and best integrated instrument available for assessing and controlling the undersea surround. Logically, then, the book proceeds to make up the most complete record to date of the development and use of undersea habitats and the tools and equipment needed for useful work on the seafloor.

It is true that we have developed and put to use surface- or remote-

controlled instrument packages capable of deeper search and, cases, more meticulous sampling and analysis than can be accom by the human diver. Beyond question, such robots will be used expanding scale in future oceanographic research; yet it is not that the insertion of humans into the waters of our world diminished in the foreseeable future. On the contrary, it probab be increased.

A major, and serious, design flaw in almost all undersea habita failure to achieve autonomy and ready mobility. Although most successfully deployed habitats are designed to operate at depths air-sea interactive forces are minimized, the dwellings are chron dependent on shore-based or surface-moored complexes to provide p respirable atmospheres, and communication links. Additionally, mo of the currently designed habitat is accomplished only by virtue dangerous and tremendously complex engineering procedure. The orig concept of a habitat for the U.S. Navy's SEALAB program wa modified nuclear submarine. For many reasons, this concept was rejec At present, in the light of the current deactivation program for o nuclear submarines, it would seem worthy of reexamination sinc would still appear to be the most flexible of all designs.

Historically, human efforts in sustained undersea existence have b very poorly chronicled. Even major efforts in this field have been record in a haphazard and anecdotal manner certain to confound t conscientious historian who seeks to prepare a credible and usef document some years downstream. In the face of these acknowledg obstacles, Miller and Koblick have persevered, and their production the best compendium available to readers with serious interest in th history of undersea habitats and the stories of their manned operations

GEORGE F. BOND
Captain (MC) USN, (Ret.)

Authors' Note: This Foreword was written in 1981. To the sorrow of his many friends and colleagues, Dr. Bond died on January 3, 1983, at the age of sixty-seven. As long-term friends, we are proud that Dr. Bond honored us by writing the Foreword to a book describing events that in many ways resulted from his vision and perseverance.

Preface

To live in and become part of the sea has long been a dream of humans, perhaps ranking second only to the desire to fly. Yet with thousands of years of intimate association with the sea, it was only in 1962 that the first aquanaut spent even a day on the ocean floor. The events described in this book are but a glimpse into the past twenty-two years of seafloor exploration during which men and women have learned to cope with the challenges and excitement, as well as the romance and frustrations, of undersea living.

This book was written not only because the course of events during the development of saturation diving and seafloor exploration merit telling but also because of the potential influence that understanding the sea can have on the success of human utilization of our precious resources. Once saturation diving and seafloor living was demonstrated to be a practical approach for working in the sea, the development and refinement of these new techniques branched into two directions: scientific and commercial. In this book, we concentrate on the problems and progress of extending seafloor bottom time in the pursuit of science. No effort has been made to review the remarkable advances made in commercial diving during the same period. The development and application of deep diving technology for use in the offshore oil and gas fields is a subject in itself and should be the focus of a separate book.

Much as the exploration of space has progressed beyond the romantic and dangerous phase of manned orbits and landings on the moon to the more prosaic, but possibly more important, stage of data gathering and evaluation, so have the techniques of seafloor living moved from the swashbuckling days of trial-and-error probing of the oceans, to more scientifically oriented and productive pursuits.

We give full credit to those pioneers who developed, sometimes at tragic cost, the knowledge and equipment that has served as the basis of the present state of the art of saturation diving and still guides its use. Based on the pioneering work of the past twenty-two years, scientific and commercial divers are able to get on with the utilization and

controlled instrument packages capable of deeper search and, in some cases, more meticulous sampling and analysis than can be accomplished by the human diver. Beyond question, such robots will be used on an expanding scale in future oceanographic research; yet it is not likely that the insertion of humans into the waters of our world will be diminished in the foreseeable future. On the contrary, it probably will be increased.

A major, and serious, design flaw in almost all undersea habitats is a failure to achieve autonomy and ready mobility. Although most of the successfully deployed habitats are designed to operate at depths where air-sea interactive forces are minimized, the dwellings are chronically dependent on shore-based or surface-moored complexes to provide power, respirable atmospheres, and communication links. Additionally, mobility of the currently designed habitat is accomplished only by virtue of a dangerous and tremendously complex engineering procedure. The original concept of a habitat for the U.S. Navy's SEALAB program was a modified nuclear submarine. For many reasons, this concept was rejected. At present, in the light of the current deactivation program for older nuclear submarines, it would seem worthy of reexamination since it would still appear to be the most flexible of all designs.

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development of ocean resources, the recovery of historical artifacts, and a better understanding of the marine organisms that inhabit 70% of the earth. We must continue to improve our capability to live and work within the sea.

JAMES W. MILLER
IAN G. KOBLICK

Chapter 1

A Brief History of Diving: Babylonia to Genesis

EARLY DAYS

The year is 2450 B.C. You're standing on the southern shore of the Persian Gulf watching two citizens of Eridu engage in their ancient trade. Glistening heads disappear from beside their boat. You see the wavering image of bodies through clear water as they sink. Less than 3 minutes later, they are gasping at the gunwale again, tossing their small harvest of pearl shells into the bottom of the boat, inhaling huge breaths for another brief visit to the sea bottom.

Business is flourishing since old King Nimrod established the Babylonian monarchy. Major cities of Mesopotamia sit like dewdrops on the cobweb of freight canals he has organized. Although demand for pearls and jewels of all kinds has never been greater, the Babylonian divers are fighting the same physical limitations as their brothers and sisters around the world. If you stood on the shore of the China Sea, the Sea of Japan, the Aegean, the Bahamas, or any of the other warm waters of the world, you would see divers forced away from their underwater work by the same barrier. Bottom time depends on how long a diver can hold his breath.

The two divers of Eridu are experts, professionals in a craft they already can trace back perhaps a thousand years. Still, even they can manage no more than 4 minutes below, and, on rare occasions, descent

may be to 150 feet (46 m). The story of diving since that time is a story of the search for extended bottom time.

Since Nimrod, divers have attacked this barrier with breathing tubes of reeds, hollowed bones, air pockets in caves, inverted buckets; necessity pushed their ingenuity to its fullest. The dream of unlimited bottom time persists throughout history.

Thucydides describes the use of military divers on a "harbor clearance" operation during an attack on Syracuse in 415 B.C. Even Alexander the Great is reported to have descended in a primitive diving bell called "Colimpha" in about 330 B.C.

In a discussion entitled "Problems Pertaining to the Ears," Aristotle (384-322 B.C.) wrote: "In order that these fishers for sponges may be supplied with a facility of respiration, kettles are let down to them in the water so that they may not be filled with water, but with air. For the descent of these kettles is accompanied with violence; so as that they may not incline to either side, but may remain perpendicular" (Larson, 1959, p. 7) This statement describes a diving bell, the principles of which became the dominant approach to underwater exploration for 22 centuries (Larson, 1959). According to Larson, nineteen hundred years passed before another reference to the diving bell was made, although unconfirmed sources credit its invention to Roger Bacon in 1250.

RENAISSANCE

In the sixteenth century, Leonardo da Vinci got into the act. As was his custom, he didn't describe his device in detail:

> "How by an appliance many are able to remain for some time under water. How and why I do not describe my method of remaining under water for as long a time as I can remain without food; and this I do not publish or divulge on account of the evil nature of men who would practice assassinations at the bottom of the seas, by breaking the ships in their lowest parts and sinking them together with the crews who are in them; and although I will furnish particulars of others they are such as are not dangerous, for above the surface of the water emerges the mouth of the tube by which they draw in breath, supported upon wine-skins or pieces of cork.
>
> A breastplate of armour together with hood, doublet, and hose, and a small wine-skin for use in passing water, a dress for armour, and the wine-skin to contain the breath, with half a hoop of iron to keep it away from the chest. If you have a whole wine-skin with a valve from the "ball,"

> when you deflate it, you will go to the bottom, dragged down by the sacks of sand; when you inflate it, you will come back to the surface of the water.
>
> A mask with the eyes protruding made of glass, but let its weight be such that you raise it as you swim [Fig. 1-1]. Carry a knife which cuts well so that a net does not hold you prisoner. [MacCurdy, 1939 in Gordon, 1972, pp. 13-14]

Good advice, followed by divers to this day. Leonardo's wet suit was a departure from the diving bell approach, but many diving bells were being tested during his lifetime. You could have seen one in Lake Nemi near Rome in 1535. According to Bert (1878), it was invented by Sturmius. Full of air, it was allowed to sink vertically until it touched bottom: "Workmen, who were ensconced up to that point on seats like shelves, got down from them to work under the worst conditions," Bert says (p. 355).

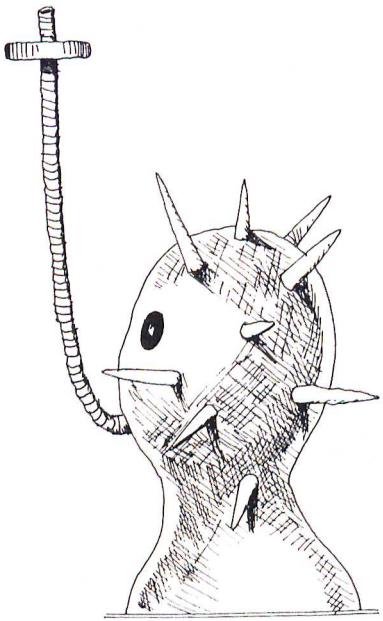

Figure 1-1. Breathing tube and underwater mask (with spikes) designed by Leonardo da Vinci. (After *The Notebooks of Leonardo Da Vinci*, edited and translated by Edward MacCurdy, Reynal and Hitchcock, New York, 1939; in Gordon, B. ed., 1972, *Man and the Sea—Classic Accounts of Marine Explorations*, Doubleday Natural History Press, Garden City, N.J., p. 13.)

SEVENTEENTH AND EIGHTEENTH CENTURIES

Bells began to take on recognizable configurations with Sir Edmund Halley's invention, a forerunner of the modern diving bell (Fig. 1-2). According to Halley (1716, in Gordon, 1972, pp. 29-30):

> The bell I made was of Wood, containing about 60 Cubick Foot in its concavity, and was of the form of a Truncate-Cone, whose Diameter at Top

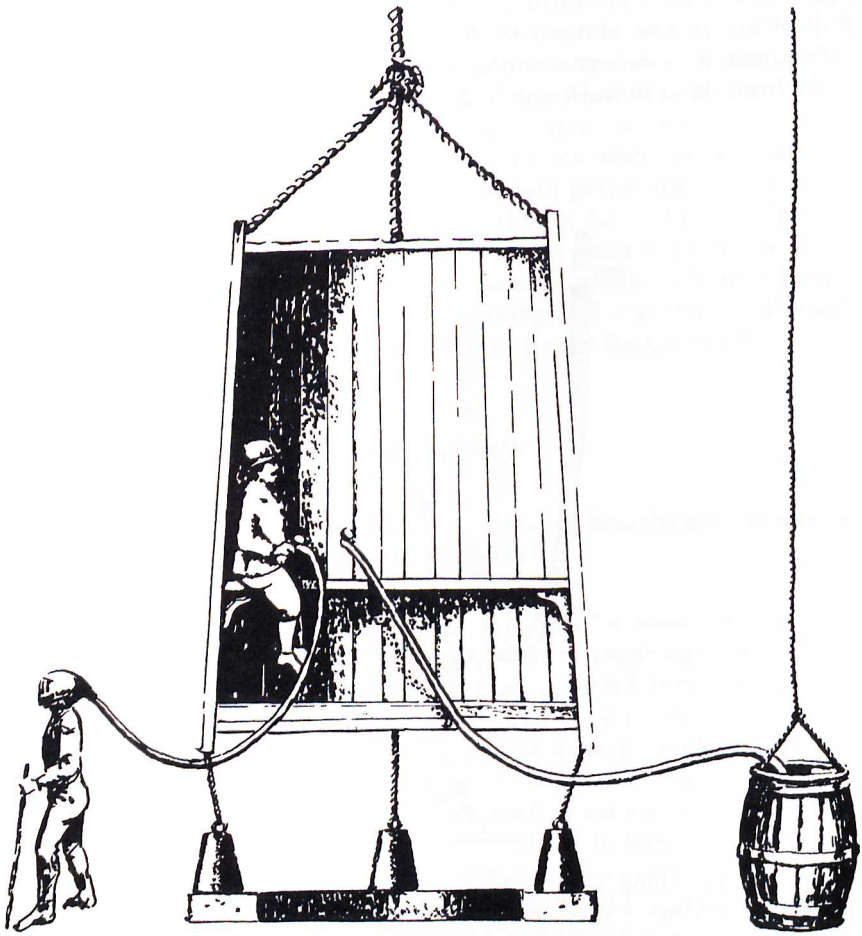

Figure 1-2. Halley's diving bell. (After Larson, H., 1959, *A History of Self-Contained Diving and Underwater Swimming*, NAS/NRC Publication 469, National Academy of Sciences, Washington, D.C., p. 10.)

> was three Foot, and at Bottom five. This I coated with Lead so heavy that it would sink empty, and I distributed the weight so about its bottom that it would go down in a perpendicular situation and no other.
>
> In the Top I fixed a strong but clear Glass to let in the light from above, and likewise a Cock to let out the hot Air that had been breathed: and below, about a Yard under the Bell, I placed a Stage which hung by three Ropes, each of which was charged with about one Hundred Weight, to keep it steddy. This machine I suspended from the mast of a Ship, by a Spritt which was sufficiently secured by Stays to the Masthead and was directed by Braces to carry it overboard clear of the Ship side, and to bring it again within board.

Air was provided by small barrels under the bell that could be opened when needed. Stale air was vented out of the top by means of a valve. Divers could even leave the bell wearing a helmet with an umbilical tube. Bert calls this the first diving system. The diving bell was by no means a dead end in the search for extended bottom time. Its principles are still used in underwater habitats and platforms.

Another direction that took shape in the late seventeenth century eventually caused a revolution in underwater work. It was developed by Giovanni Borelli. Bert (1878 p. 390) describes this device:

> It is a globe of brass or copper about two feet in diameter, placed over the head of the diver; it is fastened to a goat-skin garment made to fit the diver. In this globe are the tubes by which the circulation of the air is maintained; at his side the diver carries an air pump, by means of which he can make himself heavier or lighter, as fishes do, compressing or expanding their air-bladder: in this way he thinks he can meet all the objections made in regard to other machines, and especially the objection in regard to lack of air, since the air which has been breathed is, according to him (Borelli), deprived of its harmful qualities by circulation in the tubes.

Borelli obviously recognized the problem of CO_2 buildup, but his scrubbing system of tubes proved unsatisfactory. Another attempt to reduce CO_2 buildup was made in 1774 when a Frenchman, Freminet, devised a method of pumping a constant flow of air from the surface with a bellows. It worked for an hour at a depth of 50 feet (15.2 m) (Davis, 1962).

It was, however, an American, John Smeaton, who made the breakthrough in 1788 with an air-forcing pump that was both practical and reliable. From this point, bottom time started stretching rapidly.

BUSY NINETEENTH CENTURY

About 1819, Augustus Siebe invented an open diving dress consisting of a waist-length jacket and a metal helmet. As described in Bennett and Elliott (1975 p. 4), "Air under pressure supplied from the surface to the helmet by a force-pump could escape freely at the diver's waist." Although this design was used for several salvage operations, a serious shortcoming arose when the diver assumed other than an upright posture. Under such circumstances, there was danger of flooding the jacket and helmet.

Martin (1978) describes a diving dress patented in England in 1828 by two brothers, John and Charles Deane. This dress consisted of a helmet and a heavy suit. The helmet rested on the shoulders, held down by its own weight. It had view ports and hose connections. Air was exhausted by passing under the lower edge of the helmet, around the diver's shoulders. The Deane type of helmet would later become known generally as a shallow water helmet. Although it was used extensively for commercial, scientific, and recreational activities, it had the same serious limitation as did the Siebe suit. As Martin (p. 3) pointed out, "Should the diver trip and fall, or should he stand in other than an upright position, the helmet would either fall off entirely or be prone to flooding."

In 1837, Siebe modified and patented his open dress. The improved version was a full-length waterproof suit completely enclosing the diver except for the hands, which protruded through tight-fitting rubber cuffs that formed a seal around the wrists, as described by Martin (1978, pp. 3-4).

> A heavy rubber gasket formed a collar on the dress and was clamped to the rim of the breastplate with metal straps. The helmet was removable and secured to the breastplate by means of an interrupted joint which required one-eighth of a turn to seal the two together. A new air inlet and revised exhaust valve were incorporated into the helmet.

This diving dress, which reduced the problem of cold while increasing mobility (it did not flood), further increased the bottom time of the working diver. This suit has served as the basis for modern deep-sea diving suits, even up to the present time.

In 1865, Rouquayrol and Denayrouze invented a surface-supplied suit in which the diver did not breathe the air directly. Instead he wore a metal reservoir on his back that provided air on demand for one breathing cycle. The diver who felt particularly daring could remove the helmet and take the tube from the regulator, put it in his mouth, and breathe directly.

A succession of diving breathing systems was developed over the years

that followed, including an oxygen rebreather invented by Henry Fleuss in 1879. Aware of the danger of CO_2 buildup in exhaled air, Fleuss tried, unsuccessfully, to eliminate it by passing the exhaled air through caustic potash. Earlier attempts to remove CO_2 from exhaled air had been made by others, including Borelli and Freminet in the late eighteenth century. In 1897, Georges Jaubert tried oxylite as a CO_2 scrubber but found it to be dangerous when mixed with water. Over the years, the problem finally yielded to the work of many scientists. Now a variety of substances are used to scrub the CO_2 from exhaled air, including barium hydroxide, lithium hydroxide, and sodium hydroxide.

As is the case with most other scientific and technical advances, the solution to one problem creates several new ones. In extending bottom time through the development of air pumps, diving helmets, and scrubbing systems, divers were faced with yet another problem, decompression sickness. This malady was nothing new; it had been recognized for years by workers in tunnels and caissons. Now it was a diver's problem too. Thus the studies of scientists interested in diving medicine were added to those of engineers concerned with the safety and health of tunnel and caisson workers.

The use of compressed air to prevent water seepage into deep work areas had been suggested as early as 1691 by Denis Papin (Bert, 1878). It was not until 1851, however, that the idea was put into practice by an English engineer named Hughes during construction of Rochester Bridge over the Medway in the County of Kent. At about this same time, the French engineer Brunel used the technique to construct Chepstow Bridge over the Wye River in England.

During construction of these and other bridges, decompression sickness was noted and described. As a result, working depths were limited to 65 feet (20 m) until 1859 when workers were exposed to a depth of 85 feet (26 m) while constructing a bridge over the Nile (Bert, 1878). Tragically, this extension of depth resulted in the deaths of several workers, with the result that the problem was recognized in several countries, including England, Hungary, and France, as a very serious threat to workers.

The literature already contained descriptions of decompression sickness by engineers and other interested observers. Triger (1841) provided one of the earliest. His notes sound familiar—pain in the ears, nasal quality of speech, and joint pains (which were alleviated by rubbing the affected areas with "spirits of wine"). Triger also noted that workers were less out of breath when climbing ladders under pressure than when at the surface and that one could not whistle at pressures greater than 65 feet (20 m).

Trained physicians (M. Francois and M. Bocquoy) reviewed the prob-

lem of decompression sickness in 1859 (Bert, 1878). There were sharp differences among workers of the time with respect to their recommendations for procedures. Some insisted on slow decompression, and others thought that workers could be decompressed in 3 minutes.

What probably is one of the earliest cases of a lawsuit involving decompression sickness occurred on August 18, 1861. Bert (1878, p. 379) described the situation: "M. Gallois, civil engineer, and agent of the company, who went down into the caissons May 12, 1862 (the discrepancy in dates is Bert's); on his return to open air was attacked by symptoms of paralysis 'as result of cerebro-spinal congestions, spells of dizziness, and nervous shocks', so that he had to be sent to a watering-place: he died two years afterwards." His request for damages was refused by a tribunal on August 18, 1861. It declared that Gallois had not received an order to go down into the caisson, and thus the company could not be held responsible.

Not surprisingly, we were encountering the same decompression problems on this side of the Atlantic. In 1869 one of the first bridges constructed in the United States using the Triger method was built over the Mississippi River at St. Louis. The project was enormous and caught the imagination of the country. In the rush to complete construction, workers were exposed to depths of almost 147 feet (45 m), the deepest yet. The first deaths from decompression sickness in the United States were recorded on this job. There still was no consensus on either treatment or cure of the disease until Andrew H. Smith, the company surgeon of the New York Bridge Company, suggested the use of an above-ground recompression chamber during construction of the Brooklyn Bridge in the early 1870s. Recompression then became the accepted treatment for decompression sickness. It was 1893, however, during construction of the first Hudson River tube in New York City, before the first recompression chamber was installed and used for treating victims of the bends.

It had been a long, twisting trail since the first recognition of decompression symptoms to an understanding of their causes. Although Robert Boyle in 1660 suspected that bubbles in the circulatory system could be formed by an excessively rapid decompression, it was almost 250 years following his animal studies before such suspicions were supported by scientific experimentation.

Bert's work (1878) showed decompression sickness to be due to formation of nitrogen bubbles in blood and tissues and that the basic cause was increased partial pressure of gases in the breathing media. He recommended slow and gradual decompression as the correct procedure to use to avoid decompression sickness. He also used pure oxygen to wash nitrogen from the system. Others working with Bert's data found the same results, and his methods came into common use. Still, there were many victims of decompression sickness who did not respond to recompression.

FINALLY THE TWENTIETH CENTURY

J. S. Haldane took the next major step. Prior to Haldane, respiratory distress, occasional loss of consciousness, and compressed air illness prevented much useful work beyond depths of about 75 to 120 feet (22 to 37 m). Recognizing these limitations, Haldane, a pioneering physician in undersea medicine, designed a series of experiments to be performed in Portsmouth, England, in 1905 for the purpose of opening the way to work at depths below 108 feet (33 m) with increased bottom time. The increase in available bottom time accruing as a result of these studies, in turn, required improved methods of decompression. Haldane subsequently tackled this problem in typical thorough fashion:

> The formation of bubbles depends, evidently, on the existence of a state of supersaturation of the body fluids with nitrogen. Nevertheless, there was abundant evidence that, when the excess of atmospheric pressure does not exceed about one-and-a-quarter atmospheres (10.1m), there is complete immunity from symptoms due to bubbles, however long the exposure to the compressed air may have been, and however rapid the decompression. Thus, bubbles of nitrogen are not liberated within the body unless the supersaturation corresponds to more than a decompression from a total pressure of two-and-a-quarter atmospheres to a total pressure of one atmosphere. Now the volume of nitrogen which would tend to be liberated is the same when the total pressure is halved, whether the pressure be high or low. Hence it seemed to me probable that it would be just as safe to diminish the pressure rapidly from four atmospheres to two, or from six atmospheres to three as from two atmospheres to one. If this were the case, a system of stage decompression would be possible and would enable the diver to get rid of the excess of nitrogen through the lungs far more rapidly than if he came up at an even rate. The duration of exposure to high pressure could also be shortened very considerably without shortening the period available for work on the bottom. (Davis, 1962, p. 6)

Haldane's theory was tested extensively on goats and then humans by subjecting them systematically to increased depths until 210 feet (64 m) was reached. That was the limit at which hand pumps could supply adequate air. As a result of these tests, published by the First Admiralty Deep Diving Committee in 1905, a recommendation was made that diving with hand pumps be limited to 204 feet (62.2 m). This limit was widely adopted throughout the world.

But, all problems were not solved by this new advance. Although bottom time was extended and depth increased by Haldane's new stage

decompression tables, long immersions while holding onto a rope were a serious burden to divers already exhausted by long bottom times. To solve this drawback, Davis built a submersible decompression chamber in 1928 that allowed decompression to be carried out in relative comfort and also permitted the use of oxygen for flushing out nitrogen. The use of oxygen and submersible decompression chambers reduced decompression time to almost half and was responsible for stimulating efforts to extend working depth further.

Through a series of experiments with animals and, later, humans, it was found that Haldane's system of reducing pressure by half for decompression stops could not safely be extended to 300 feet (91.5 m), the target depth at that time.

By reducing the 2-to-1 ratio to 1.75 to 1 and using appropriate oxygen cleansing, a new schedule was developed under Captain G. C. C. Damant of the Royal Navy and Siebe, Gorman and Co., Ltd. (Davis, 1962). Divers could then use Haldane's tables to depths of 210 feet (64 m) and the Damant method on down to 300 feet (91.5 m).

Although the experiments of Bert, Haldane, and others resulted in significant advances in our understanding of diving physiology, diving technology was still in its rudimentary stage. It took a U.S. Navy warrant gunner in 1912 to open the U.S. Navy's eyes to the sad condition of their diving training and equipment. In a report submitted to the Bureau of Construction and Repair, Gunner George T. Stillson suggested a series of experiments based on those the British Admiralty had conducted in 1906 and 1907. Acting on Stillson's report, the navy initiated a diving research program. In 1913, over three hundred test dives were conducted up to depths of 258 feet (78.7 m) at the new U.S. Navy Experimental Diving Station, New York Naval Shipyard, Brooklyn.

These tests revealed inadequate air supply as the primary cause of the stress navy divers had been experiencing at depth. As a result of these studies, hand pumps were replaced by compressed air, and the Admiralty decompression tables were recommended for adoption. Another spinoff of Stillson's report was the establishment of the navy's first deep-sea diving school at the U.S. Naval Torpedo Station in Newport, Rhode Island, in 1916. Eventually the first diving manual evolved from this school and was published in 1924 by the Bureau of Construction and Repair.

The new diving capability of the navy received its first test in 1915 when the navy submarine F-4 sank in Amala Bay off Honolulu. The deep diving tests made in 1913 paid off during search and salvage operations, allowing dives from 42 feet (12.8 m) to 306 feet (93.3 m) to be made safely.

A strange and unexpected aspect of deep diving now made its appearance. Today we know it as nitrogen narcosis, but when the first divers began experiencing inappropriate cheerfulness, confusion, and memory failure,

the symptoms were attributed to increased oxygen pressure and buildup of carbon dioxide in the divers' helmets. It was to be 1935 before Behnke, Thomson, and Motley pinned down increased nitrogen pressure as the true culprit.

In 1917, Clarence Tibbals initiated a series of experimental dives involving the use of mixed gases—nitrogen, helium, and oxygen. The work showed promise, and by 1922 Tibbals was supervising an experimental diving program from the U.S.S. *Falcon,* which included at least one helium-oxygen dive to a depth of 150 feet (45.7 m).

Helium had been suggested as a breathing medium for divers under pressure as early as 1919 by C. J. Cooke, but at that time its cost was prohibitive—around $2,500 per cubic foot in 1915. By the time Tibbal's work on the *Falcon* was underway, the cost of helium had dropped dramatically to three cents per cubic foot. This cheap supply of helium stimulated experiments in the use of helium-oxygen breathing mixtures to prevent aberrant mental behavior found during deep dives with nitrogen (Penzias and Goodman, 1973).

While the safe increase in bottom time was a primary goal of many investigators, there were some whose work was directed toward gaining self-sufficient mobility. In 1926 Fernez and Captain Yves Le Prieur developed a self-contained breathing unit that in 1933 was improved by Le Prieur. The revised model included a full-face mask instead of goggles, a mouthpiece, and a nose clip. The diver was beginning to look like a modern aquanaut but could submerge only for about 30 minutes at a time before the steady flow of air depleted his reserve tank.

With the outbreak of World War II, interest shifted from the experimental to the practical, especially in the military use of self-contained diving gear. Looking back to the diving apparatus patented by Le Prieur and Fernez, military applications could be imagined easily. Such a system was described by Larson (1959, p. 33):

> This apparatus included a steel cylinder of three liters' capacity into which air was compressed 1700-1950 pounds per square inch (120-150 kg/cm_2). The cylinder was worn on the back, with a short air hose leading to a mouthpiece held in the diver's mouth, and a pressure gauge jutting out over the left shoulder. The diver wore small, tight goggles and a nose clip. This apparatus weighed about 20 pounds (9.1 kg) and reportedly allowed a little over 10 minutes under water.

About this same time, swim fins were invented by Commander de Corlieu, also of the French Navy. The fins permitted scuba to be used in the natural swimming position for the first time since Borelli's system in 1680.

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During World War II, military divers also were investigating closed-circuit breathing systems that left no bubbles. Two Italians, Lieutenants Teseo Tesei and Elios Toschi, had suggested the use of scuba-equipped torpedo riders as a weapon against enemy ships. They even had initiated a small program in the Italian Navy to this end in 1935, but it was abandoned quickly, possibly from lack of volunteers. When war broke out in 1939, this program was resurrected, and diver attack units were used by the Italian Navy until their surrender in 1943. Their breathing equipment was an oxygen rebreather utilizing soda lime to remove CO_2, a process that gave the diver an underwater time of 6 hours. During one successful raid in September 1941, the Italian divers sank three British ships (Penzias and Goodman, 1973).

This success stirred interest in other countries, including the United States where the LARU (Lambertsen Amphibious Respiratory Unit) was developed. The LARU was a semi-closed-circuit, steady-flow oxygen rebreather developed by Dr. Christian J. Lambertsen of the University of Pennsylvania, which was used by the Office of Strategic Services and the U.S. Navy in wartime operations (Lambertsen, 1941).

In 1943 a Frenchman named Jacques-Yves Cousteau, along with his countryman Emile Gagnan, made a small modification to the self-contained breathing system; they introduced a demand intake valve into the system that released air to the diver only when needed, greatly increasing the available bottom time. This invention became the famous Aqua-Lung, which opened the underwater world to millions (Dugan, 1965). Although the system was unsuitable for military use due to the telltale trail of bubbles, the Aqua-Lung became the main booster for the sports-diving market that took off after the war.

After World War II, interest in experimental deep diving was rekindled. At the Admiralty Experimental Diving Unit in Portsmouth, England, a series of 52 experimental dives was conducted using air, followed by a series of 18 helium-oxygen dives. As a result of these dives, it was concluded that the maximum safe depth at which air should be used as the breathing gas was about 250 feet (76 m). By contrast helium-oxygen dives were carried out safely to depths up to 535 feet (163 m). The level of diving activity in the U.S. Navy also increased significantly after the war. It was summed up briefly in the 1970 edition of the U.S. Navy Diving Manual (p. 16):

> During and after World War II, the Experimental Diving Unit continued the improvement of helium/oxygen equipment and techniques. Dives as deep as 561 feet were made using helium/oxygen gear in wet pressure tanks, research in other aspects of diving also continued. One notable advancement was the development of tables for surface decompression after air dives, using oxygen to appreciably shorten decompression time.

The search for increased bottom time has stretched through four thousand years of human history, from our pearl diving ancestors to the helium-oxygen divers of today. In spite of this long history of diving, laboratory studies, and wartime operations, time on the bottom continued to be measured in minutes and on a few occasions in hours. The concept of spending days, months, or even years on the seafloor was only a dream in the minds of a few. As early as 1942, however, the possibility of remaining under pressure long enough to allow the blood and tissues to become fully saturated with breathing gases was being considered (Behnke, 1942). Such a possibility was raised initially within the context of reducing the number of decompressions required in tunnel and caisson operations rather than diving. In 1942 Behnke commented:

> From the point of view of physiologic response and work output, the attempt to decompress men twice daily is not only potentially dangerous but also highly uneconomical . . . it would appear advisable therefore to keep men at work on a job continually under pressure. Following a work shift at maximum pressure, the pressure could be lowered rapidly to between 20 and 30 psi and maintained at this level during the rest and sleep period. (In Penzias and Goodman, 1973, p. 57)

Behnke was suggesting that it should be possible to saturate the blood and tissues fully with breathing gases at a given depth and make excursions to work at a greater depth. But it was to be another twenty years before this concept, subsequently referred to as saturation diving, was tested operationally at sea.

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Chapter 2

Project Genesis: of Mice and Men

The idea of exposing humans to increased ambient pressures for periods long enough to allow the blood and tissues to become fully saturated with inert gases was conceived in 1942 as a means of improving the effectiveness and safety of tunnel and caisson operations (Behnke, 1942). It was 1957, however, before the first experimental studies addressing this concept began. Before reviewing these pioneering laboratory experiments, let's consider briefly the relationship between the saturation of blood and tissue and living in the sea.

A sponge immersed in a liquid will continue to absorb the liquid until it is totally saturated. Once saturation occurs, continued immersion, whether for hours or weeks, will not increase the amount of liquid that ultimately can be wrung from the sponge on removal. Now let's suppose a diver exposed to increased atmospheric pressure at a constant depth is substituted for the sponge. Once the blood and tissues become fully saturated with the inert breathing gases, usually nitrogen or helium, the decompression time required to remove those gases at the end of the exposure does not increase with additional time spent at that depth. The time required for total saturation to occur varies, however, depending on the composition of the breathing gases, the ultimate depth of exposure, and the speed at which that depth is attained. While total saturation is a lengthy process it is, for the most part, complete within about 24 to 36 hours.

Final decompression time also changes as a function of the type of breathing gas and the depth: the greater the depth, the longer the decompression time. Whether for purposes of work, science, or exploration, the utilization of what we now refer to as saturation diving permits virtually unlimited exposure to increased pressure with only a single decompression required at the end. It is the demonstration of this concept that has made it possible for air-breathing humans to live and work in the sea.

The pivotal character in the laboratory studies that transformed saturation diving from concept to reality, which began in 1957, was Dr. George F. Bond (Fig. 2-1). Bond was a practicing physician in Bat Cave, North Carolina, when he became concerned with a possible world shortage of animal protein. Combined with an interest in the sea, this concern led him

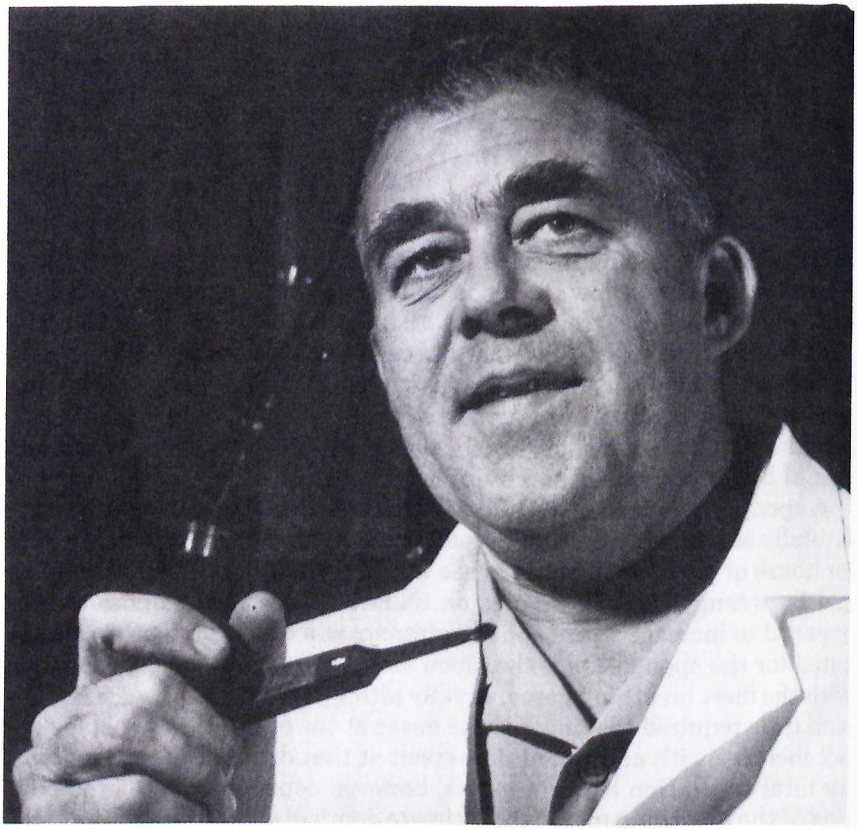

Figure 2-1. Captain George F. Bond. *(Courtesy of U.S. Navy.)*

to studies of the nutritional and economic potential the sea might provide. On entering the navy in 1953, his interests influenced him to specialize in submarine medicine.

By 1957, Bond was assistant officer in charge of the Naval Submarine Medical Research Laboratory at New London, Connecticut, where the main emphasis at the time was on submarine escape. Although not central to his interests, the work did require his involvement in studies of underwater breathing gases, bottom time limitations, and the development of advanced breathing gas mixtures. These interests of the navy also were important to Bond's feeling that if humans were to survive on this planet, they would have to enter the underwater world and remain there to explore, observe, and harvest the wealth of the oceans.

The dreams of Dr. Bond and the goals of the U.S. Navy coincided in Project Genesis, a program that began in 1957 with the purpose, according to Bond, of ". . . expansion of man's ability to utilize the products of the marine biosphere which make up nearly three quarters of our Earth" (Bond, 1964, p. 311). Bond named this project Genesis because he saw it as an important step toward attaining the "dominion over the sea" promised in the Book of Genesis.

The first phases of Genesis, conducted on a part-time basis during 1957-1958, concerned the prolonged exposure of laboratory animals to high pressure and various breathing gases. These experiments were referred to as Genesis phases A and B. All of the Genesis experiments were conducted using laboratory chambers in which the pressure could be elevated to simulate increased depths of water. Problems encountered immediately were the choice of breathing mixtures and the decompression procedures to be used following total body saturation with the gas breathed. A gas mixture ultimately was needed that would minimize both narcosis and breathing resistance.

PHASE A—SATURATING RATS IN AIR AND OXYGEN

In phase A1, selected Wistar strain rat populations were exposed to a depth of 198 feet (60.4 m) using compressed air as the breathing medium. At the end of 35 hours, all the rats were dead. The postmortem examinations revealed that the deaths were attributed to continuous exposure to high oxygen partial pressure (1.4 ATA).

In another study, phase A2, equivalent groups of rats were exposed to a depth of 198 feet (60.4 m), in this case using a breathing mixture in which the partial pressure of oxygen was held at 0.21 ATA or 3% of the breathing gas, with nitrogen making up the remaining 97% of the mixture. Although all but one of the 16 animals survived the 14-day exposure,


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specific and irreversible lung lesions were found in all survivors (Bond, 1964). The lesions generally were attributed to the density of the breathing mixture, although consideration was given to the narcotic effect of nitrogen, which could have altered normal respiratory patterns.

For a final check, phase A3, on the effects of elevated oxygen partial pressures, another matching rat group was exposed to a depth of 45 feet (13.6 m) under similar conditions of temperature and humidity. In this experiment, the breathing gas was 100% oxygen, which was equivalent to the oxygen partial pressure (1.5 ATA) used during the initial experiment at 198 feet (60.4 m) resulting in the death of all the original rats. The results were the same as in phase A1: all of the rats died after 35 hours.

The Genesis phase A experiments demonstrated clearly that death was caused by the lethal effects of breathing oxygen under high pressure. It was obvious that oxygen had to be mixed with an inert gas in order to provide a safe breathing mixture.

Because of the known narcotic effect of breathing high concentrations of nitrogen under pressure, it was necessary to select the most appropriate inert gas with which to mix oxygen during extended exposures to pressure. Helium was the obvious choice because of its long history of use as a breathing medium for U.S. Navy divers, beginning with experiments in 1924. Thousands of hours of human exposure to breathing mixtures of helium-oxygen were on record. Still, many competent physiologists believed that atmospheric nitrogen is essential to mammalian life. To refute or confirm this belief, it was necessary to conduct animal experiments in which nitrogen was absent in the breathing gas. Accordingly, the next series of Genesis experiments was undertaken.

PHASE B—RATS, GOATS, AND MONKEYS TRY HELIUM AND OXYGEN

A large colony of rats breathed a mixture of 80% helium and 20% oxygen at the surface for 16 days. Postexperimental examinations revealed no immediate or delayed adverse physiological effects. Subsequently a long series of helium-oxygen exposures was carried out, which became known as Genesis phase B1. The completion of the phase B1 program led directly into the next phase.

In phase B2, rats were exposed to a depth of 200 feet (61 m) for 14 days with a breathing medium of 3% oxygen and 97% helium during which extensive biochemical, physiological, and histopathological studies were carried out. All subjects survived, and no immediate adverse physiological effects were noted during or after the experiment. The life span and

breeding characteristics of the animals subsequently were checked and found to be normal (Bond, pers. commun., 1981).

Experiments were extended to four more species, including goats and squirrel monkeys (phase B3). After two additional years of successful experimentation, it was reported that all animals exposed to a selected mixture of helium-oxygen and lesser quantities of inert gases not only survived a 14-day exposure at a simulated depth of 200 feet (61 m) but could safely be returned to sea level with no physiological damage. Decompression problems and treatment of decompression accidents involved in such exposures were clarified in a separate series of experiments. This concluded Genesis phase B.

Bond's studies attracted the attention of Captains Walter F. Mazzone and Robert W. Workman of the U.S. Navy in late 1958. They became training officer and assistant officer in charge, respectively, in 1959. Captain Mazzone also assumed the collateral duty as project officer for Genesis.

After additional studies on animals at the Submarine Medical Research Laboratory, Bond and his two colleagues submitted a proposal to the navy based on the animal work recommending that experimental studies be carried out using human subjects. Bond felt that humans could live and perform useful work to depths of 600 feet (183 m) for periods in excess of 30 days. The proposal also described how submarines could be modified to provide an underwater mobile base for divers and how it would be possible to establish fixed underwater stations. Examples of scientific disciplines that would benefit from an underwater laboratory included marine biology, marine botany, oceanography, and physics, the last through the establishment of a radiation-free laboratory. Other uses of underwater stations suggested included deep sea salvage, underwater construction, oil and natural gas exploration, and numerous military applications. The proposal was submitted to the Bureau of Medicine and Surgery and was promptly turned down. Months later the Office of Naval Research became interested in the project and helped Bond prepare a presentation to the secretary of the navy for Research and Development. The presentation was well received (Bond, pers. commun.).

PHASE C—HUMANS LIVE IN HELIUM FOR SIX DAYS

In 1962 Secretary of the Navy Fred H. Korth granted permission to use human subjects for an extended exposure to what essentially was a nitrogen-free atmosphere. This experiment was referred to as phase C of Genesis I. In this study, two submarine medical officers, Lieutenants

John C. Bull, Jr., and Albert P. Fisher, Jr., together with a veteran Navy diver, Chief Quartermaster Robert A. Barth, were exposed to helium-oxygen breathing gas at a pressure of 1 atmosphere (surface) for a period of 6 days at the navy's New London laboratory. The average composition of the breathing medium was 21.6% oxygen, 4.0% nitrogen, and 74.4% helium (Bond, 1964). As in the case of the animal experiments, all parameters of blood chemistries and morphologies were evaluated carefully. Electrocardiograms, electroencephalograms, metabolic values, and a multitude of psychophysiologic tests were administered. Throughout the 6-day exposure, the men were under observation and were checked for visual acuity, color perception, auditory abilities, and voice characteristics.

Due to the extensive base of animal experiments, there were no unhappy surprises in Phase C. As expected, the large amount of helium changed speech to the familiar "Donald Duck" voice, although after 2 days, the men adjusted and were able to communicate adequately.

Although no measurable physiological decrement was found, the data indicated a problem with body temperature control. As a consequence, the subjects preferred a rather high ambient temperature in the pressure chamber of about 88°F (31°C). This preference subsequently was found to be commonplace for those living in a helium environment because helium conducts heat approximately six times more than does air. Thus, a significantly greater amount of body heat is lost from the skin and during each exhalation when one is immersed in a helium atmosphere. Although these findings were of interest, phase C was considered a success and to have demonstrated that humans can exist for at least 6 days in an environment lacking an appreciable amount of nitrogen.

PHASE D—HELIUM SATURATION AT 100 FEET

Phase D of the Genesis experiments took place during April 1963 at the U.S. Navy Experimental Diving Unit in Washington, D.C. (Anon., 1963; Geremia, 1963). Unlike phase C, where the human subjects remained at the surface, phase D was to expose the men to a pressure equivalent to 100 feet (30.5 m) of seawater. The breathing mixture again was mostly helium: 7% oxygen, 7% nitrogen, and 86% helium (Bond, 1964). Three 32-year old navy enlisted men—Robert Barth, Sanders W. Manning, and Raymond R. Lavois—entered the pressure chamber at 4:00 P.M. on April 22, and lived for 6 days in a dry compartment 12 feet (3.7 m) long and 6 feet (1.8 m) in diameter connected to a cylindrical wet room 10 feet (3 m) in diameter and 18 feet (5.5 m) deep. Periodically the men entered the wet room, where water temperature was kept at 92°F (33.3°C), to swim underwater and to perform energy-consuming work. Their dry chamber

was equipped with an electric stove, a refrigerator, a toilet, special fans to purify and to keep the atmosphere circulating, as well as reading material and a TV set to relieve the boredom of their confinement.

Phase D confirmed what phase C had suggested: humans could live at depth for several days breathing a mixture of helium, oxygen, and nitrogen. This was the world's first saturation dive in which humans had remained under elevated atmospheric pressure for more than a few hours. The body temperature control problem encountered in phase C was experienced again, as were the difficulties of communication, which were even worse because of the greater ambient pressure.

PHASE E—TWELVE DAYS AT 198 FEET

Phase E, the final series of the Genesis laboratory tests, was conducted during August and September 1963 at the Climate-Altitude Chamber at the Naval Submarine Medical Research Laboratory in New London, where phase C had been completed in 1962. During phase E, Dr. John C. Bull, Robert Barth, and Sanders W. Manning spent 12 days at the simulated depth of 198 feet (60.4 m) (Fig. 2-2). The breathing mixture



Figure 2-2. Principal participants in Genesis Phase E. Left to right: Walter F. Mazzone, John C. Bull, Robert A. Barth, Sanders W. Manning, and George F. Bond. *(Courtesy of U.S. Navy.)*

was 3.9% oxygen, 6.5% nitrogen, and 89.6% helium (Lord, Bond, and Schaefer, 1966).

Physiological and psychological tests were expanded, with approximately one hundred items of psychophysiological data being obtained from each subject. The only measures found to fall outside normal limits were conventional stress indicators, reflecting the hazardous exposure experienced by the subjects, as well as stress caused by many mechanical and material failures of the diving system itself during the 12-day experiment. Bacteriologic studies of fecal and oral samples failed to reveal development of pathogenic strains or shifts of bacterial balance during the tests. Similarly, no evidence of alteration in respiratory quotients of the subjects was found.

The now-familiar problems of thermal balance and voice communication reappeared. With 80% relative humidity in the chamber, the subjects were uncomfortably cold at a temperature less than 91°F (32.7°C). Communication among subjects in the chamber was difficult, and communication between subjects and outside observers was virtually impossible. The last 27 hours of the 12-day exposure were spent decompressing back to the surface using the method of linear ascent. Lord, Bond, and Schaefer (1966, p. 1838) concluded:

> During the 12-day exposure to 7.0 Ata in 90% helium, the subjects remained alert and symptom free. None of the manifestations of oxygen toxicity were evident even though the ambient oxygen partial pressure was above normal. After 10 days the changes in expiratory flow were the same as during an acute exposure. Thus, there is no evidence for any progressive decrement in gas flow during prolonged high pressure exposure to helium.

Genesis was finished, completing the laboratory studies of the U.S. Navy's Man-in-Sea Program. The results of the Genesis experiments are summarized in Table 2-1.

Dr. Bond (1964, p. 314) summed up,

> As a result of some six years of animal and human studies involving closed ecological systems, elevated pressures, and synthetic atmospheres, the stage has been set for operational application of the work. It would now appear that we can safely station men at any point on the submerged continental shelf, with a reasonable expectancy of useful performance for prolonged periods of time.

Finally, after over forty-five hundred years of frustratingly short visits under the sea, we now could look forward to the ultimate colonization of the world's oceans.

Table 2-1. Summary of Genesis Experiments

Genesis Phases	*Date*	*Location*	*Subjects*	*Depth (Feet)*	*Duration*	*Breathing Mixture(%)*	*Major Problems*
A1	1957	NMRL[a]	Rats	198	35 hrs.	compressed air	All died
A2	1957	NMRL[a]	Rats	198	14 days	3.0 O_2 97.0 N_2	1 died; survivors had lung lesions
A3	1957	NMRL[a]	Rats	1.5 ATA (surface)	35 hrs.	100.0 O_2	All died
B1	1957	NMRL[a]	Rats	1 ATA (surface)	16 days	20.0 O_2 80.0 He	All survived
B2	1957	NMRL[a]	Rats	200	14 days	3.0 O_2 97.0 He	All survived
B3	1958	NMRL[a]	Rats, goats, squirrel monkeys	200	14 days	3.0 O_2 97.0 He	All survived
C	1962	NMRL[a]	Human (3 subjects)	1 ATA (surface)	6 days	21.6 O_2 4.0 N_2 74.4 He	Speech/thermal
D	1963	EDU,[b]	Human (3 subjects)	100	6 days	7.0 O_2 7.0 N_2 86.0 He	Speech/thermal
E	1963	NMRL[a]	Human (3 subjects)	198	12 days	3.9 O_2 6.5 N_2 89.6 He	Speech/thermal

[a]Naval Submarine Medical Research Laboratory, New London, Conn.
[b]U.S. Navy Experimental Diving Unit, Washington, D.C.

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Chapter 3

Surviving in the Sea

Captain George Bond's successful Genesis experiments with animals and humans provided a powerful boost to undersea exploration. As a result of the navy's experiments, explorers, ocean engineers, specialists in diving medicine, and others now realized that a single decompression after long work periods on the bottom would reduce the incidence of bends, thereby increasing the safety and flexibility of deep sea operations.

One undersea explorer intrigued with Bond's findings was inventor Edwin A. Link. During the fifties, Link, engaged in underwater archaeology, became increasingly frustrated by the short bottom times restricting his divers. In 1956, he submitted to a committee of the Smithsonian Institution an outline of his goal "to put man in the sea, safely, deep and long enough to enable him to do useful work" (Stenuit, 1966, p. 14). He revealed for the first time the blueprints of his diving capsule, the Link cylinder. This plan called for a diving system that would allow divers to work on the bottom for long periods and then be brought to the surface under pressure and safely decompressed there. The principles in the concept of a submersible cylinder were not new, but the broad applications Link envisaged were.

Bond had demonstrated in early 1962 that rats could survive at depths of 198 feet (60.4 m) for extended times when breathing a mixture of helium-oxygen and that humans could survive on helium-oxygen mix-

tures at the surface. After reviewing Bond's animal studies, Link decided to conduct open-sea experiments using human subjects. This first system, designed for prolonged submergence in the open sea, was developed and implemented with support from the National Geographic Society and the cooperation of the Smithsonian Institution (Link, 1963).

The first program was to take place 8 months before the U.S. Navy began its chamber tests in New London in which humans were exposed to simulated depths of 100 feet (30.5) on helium-oxygen. Link's 3×11 foot (0.9×3.4 m) cylinder was constructed of aluminum and was designed to hold one person to depths as great as 400 feet (122 m) (Fig. 3-1). It was equipped with two pad eyes at the top for lifting and handling and through-hull fittings for the life-support umbilical. The latter was composed of communication, breathing gas, and atmospheric monitoring hoses. Emergency gas supply tanks, an anchor weight, and a winch were mounted externally. The total weight, including ballast, was 4200 pounds (1905 kg). As shown in Fig. 3-1, the cylinder had two compartments and

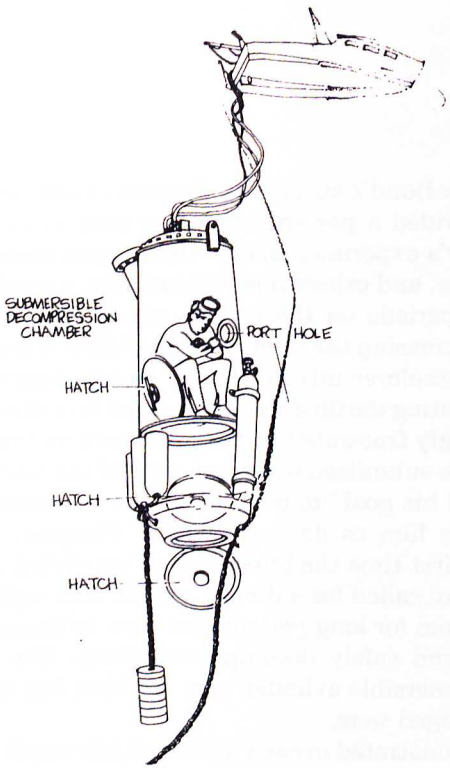

Figure 3-1. Submersible decompression chamber used in Man-in-the-Sea I. *(After J.B. MacInnis, 1966, Living under the Sea, Sci. Am.* ***214****(3):24.)*

three watertight hatches. It was not a place for a claustrophobic; the outer air lock was only 4.5 feet (1.4 m) long and the main living compartment 71 inches (1.8 m) long. According to Link, "My little 'sea bungalow' has all the modern conveniences: electric light, heating, air conditioning, telephone. The breathing mixture is supplied from the ship, and exhausted atmosphere is returned to it, by means of two hoses. No face mask is necessary inside the cylinder" (Kilbracken, 1963, p. 721).

Following a series of short dives in the cylinder, on August 19, 1962, Link moved his support vessel *Sea Diver* into Villefranche Bay on the French Riviera in the Mediterranean Sea for the dive that would complete the first phase of his program. Arriving at the dive site on August 27, the *Sea Diver* was anchored, and Link made a trial dive to a depth of 35 feet (10.7 m). After 2 hours, the cylinder was hoisted back on deck with Link inside, where he remained for the 20-minute decompression. Based on this success, it was decided to conduct phase 1 the following day.

On August 28 at 8:21 A.M. the cylinder was lowered over the side. Link himself, at age 58, made the first prolonged submergence using his one-man chamber (Fig. 3-2). He spent 8 hours at a depth of 60 feet (18.3 m) breathing a mixture of 10% oxygen, 87% helium, and 3% nitrogen.

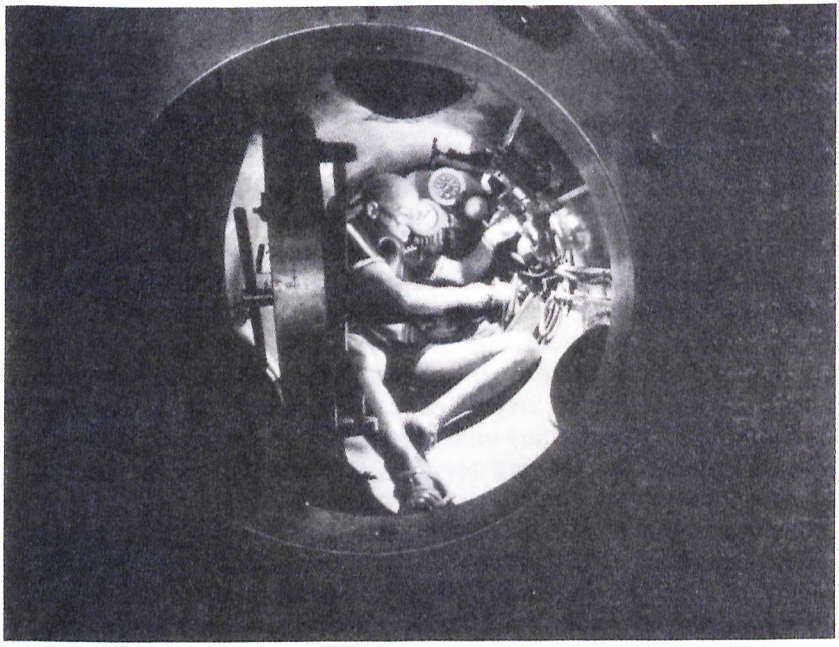

Figure 3-2. Inventor Edwin Link in his undersea cylinder. *(By Thomas J. Abercrombie; © 1963 National Geographic Society.)*

During this period, he worked in the water for 90 minutes. Mail, food, and coffee were delivered to him by his son Clayton. A hypodermic needle was used in the cylinder to equalize pressure in the coffee flask. At the end of 6 hours, the hatches were closed, and the 6-hour decompression began on the seafloor. With 2.5 hours of decompression remaining, the cylinder was returned to the deck, where it was placed in a horizontal position, allowing Link finally to lie down. At 11:35 P.M., 14 hours and 20 minutes after entering the cylinder, Link crawled out in good spirits (Kilbracken, 1963). No ill effects were observed during the exposure or after completion of decompression (Bennett and Elliott, 1975).

MAN-IN-THE-SEA I, 1962

With the successful conclusion of his first experiments, Link immediately set up a second project, Man-in-the-Sea I, the first open-sea test of the Genesis series of laboratory experiments. Plans called for one diver, Robert Stenuit, to spend 48 hours in Link's cylinder at a depth of 200 feet (61 m) (Stenuit, 1966). He would be breathing 3% oxygen and 97% helium.

Link moved *Sea Diver* to deeper water and prepared for his pioneering effort. Stenuit arrived in Villefranche on September 2 to begin training dives and become familiar with the diving system. Four days later, on the morning of September 6, Man-in-the-Sea I began.

The cylinder was lowered horizontally over the side of the ship with a variety of booms and slings and much muscle power (Fig. 3-3). Once it was in the water, the hatch end was lowered until the chamber was vertical. When preparations were complete, Stenuit entered the chamber at the surface and took up residence. It was like being locked in a storm sewer. The cylinder was lowered to a depth of 200 feet (61 m) and pressure equalized to ambient depth from inside by Stenuit. The hatch then was opened, allowing him to exit the chamber. During his stay on the bottom, Stenuit left the chamber several times for simulated work and once to bring in dinner from a lowered canister. He was able to dive within a radius of 50 feet (15.2 m) and to make ascending and descending vertical excursions to 190 and 243 feet (57.9 and 74.1 m), respectively (Stenuit, 1966).

Although the dive had been scheduled to last 48 hours, it was aborted after 24 hours and 15 minutes due to helium leaks in the breathing system, weather conditions, and logistic difficulties. Stenuit, however, had become the world's first aquanaut, an individual who remains on the seafloor continuously for 24 hours or more. The marginal handling capability of the ship permitted recovery of the heavy chamber only in

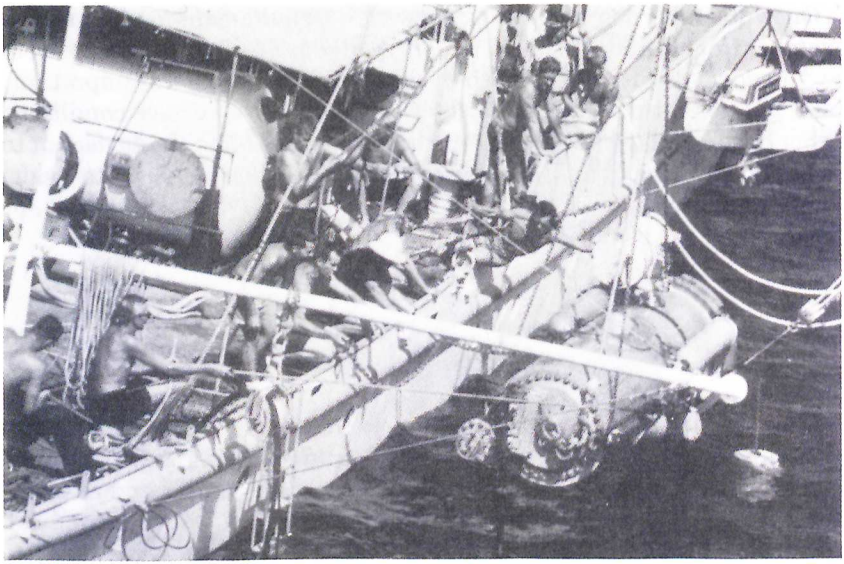

Figure 3-3. Launching the submersible decompression chamber, Man-in-the-Sea I. *(By Bates Littlehales; © 1967 National Geographic Society.)*

relatively calm seas, and bad weather was predicted. The dive could have been put on hold to wait out the weather if the small boat carrying the project's replacement helium supply had not swamped and sunk near the dive site (Kilbracken, 1963).

Informed of the abort, Stenuit sealed the outside hatch and reduced internal pressure to 100 feet (30.5 m), the depth of the first decompression stop. The chamber then was raised and brought aboard the *Sea Diver* ahead of the approaching storm. A pain in Stenuit's right wrist forced the decompression time to be lengthened from 53 to 65.5 hours and recompression to 75 feet (22.9 m). In Stenuit's words:

> This first long dive established that the purpose for which the cylinder had been designed could be fulfilled in practice. The same vessel had been an underwater elevator, a shelter, an SDC [submersible decompression chamber] and a decompression chamber on deck. The helium oxygen mixture had produced no ill-effects during the saturation dive and I found the chamber, although cramped, suitable as a refuge during the period concerned. Now we were ready to move on to the second part of the experiment—to penetrate deeper into the sea and stay living and working there longer. [Stenuit, 1966, p. 15]

One vulnerable point of the system was the requirement to suspend the chamber from the support ship for long periods, which forced recovery to be dependent on prevailing weather and sea conditions. It was important, Link felt, for future aquanauts to be independent of surface conditions either by remaining on the seafloor with no connection to the surface or to be provided with a system capable of quickly transferring them to a safe, comfortable pressure chamber aboard ship where they could wait for weather and sea conditions to improve.

CONSHELF I, 1962

Link was not the only one who had followed the Genesis experiments with great interest. The French also had been monitoring Bond's studies and now were preparing, under the Office Français de Recherches Sous-Marines, a program called Pre Continent I or Conshelf I to be carried out under the direction of Jacques-Yves Cousteau.

Four days following the termination of Link's Man-in-the-Sea I, Conshelf I was begun off the coast of Marseilles, only 100 miles (161 km) from Link's site. Conshelf I spanned 1 week—September 14 through 21, 1962—and marked the first time humans lived on the seafloor.

This first underwater habitat, named Diogenes, was an 8 × 17 foot (2.4 × 5.2 m) steel cylinder anchored to the seafloor with huge blocks of pig iron and heavy chains (Fig. 3-4). Placed at a depth of 32.8 feet (10 m), Diogenes had an entrance trunk in the floor that allowed the two aquanauts, Albert Falco and Claude Wesly, easy access to the sea. As with the Man-in-the-Sea I and all future habitats, the pressure inside was slightly higher than that of the surrounding water to prevent water from entering the habitat in the same manner as it prevents a glass from becoming filled when it is inverted and immersed in a liquid.

Support ships on the surface supplied Diogenes with hot water through a plastic tube. Food was transferred from the surface in watertight containers, called transfer pots, in much the same manner as in Man-in-the-Sea I. The remaining life support, consisting of electricity to operate the four infrared lamps used for heat, the radio and phonograph, three telephones, and a closed-circuit TV system, was supplied from a shore base on the nearby island of Frioul. In addition to these amenities, Diogenes contained two bunks, as well as eating and storage areas (Fig. 3-5).

The breathing medium was compressed air, both in the "house" and in the aqualungs used during excursion dives (Aquadro and Chouteau, 1967). The two men worked in the water for as long as 5 hours at a time

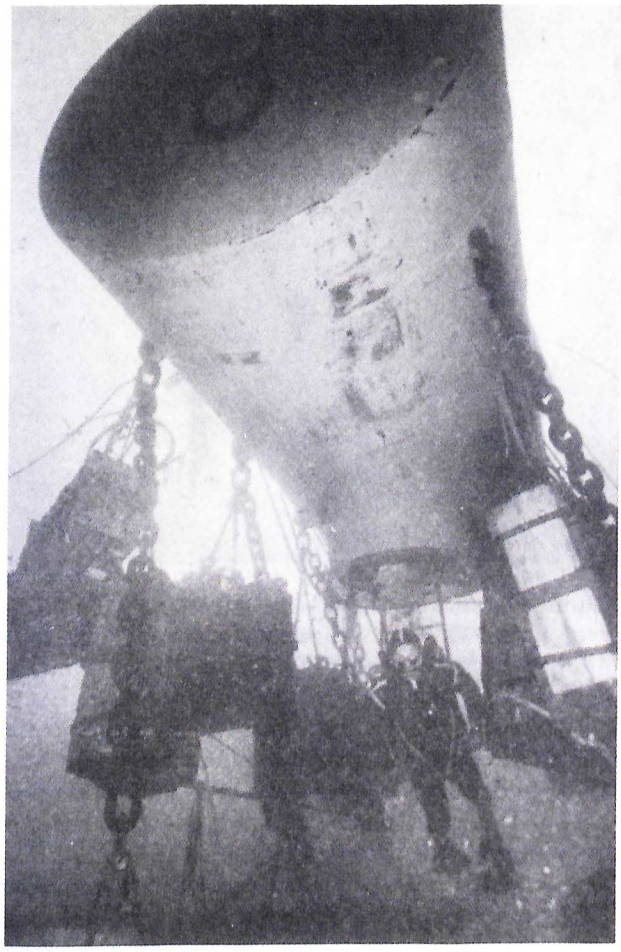

Figure 3-4. Exterior of The Conshelf I Habitat, Diogenes. *(Courtesy of The Cousteau Society, Inc., 930 West 21st Street, Norfolk, VA 23517, a membership-supported environmental organization.)*

and descended to depths as great as 180 feet (54.9 m). Water temperatures ranged from 61° to 70°F (16° to 21°C).

During their 7-day mission on the ocean floor, Falco and Wesly built fish houses using cement blocks and constructed an underwater fish pen using steel mesh. Fish were captured and placed in these pens and their behavior photographed (Cousteau, 1965). The aquanauts also conducted surveys of underwater topography that required them to measure depth and distances and to determine angles. These data were used to lay out a

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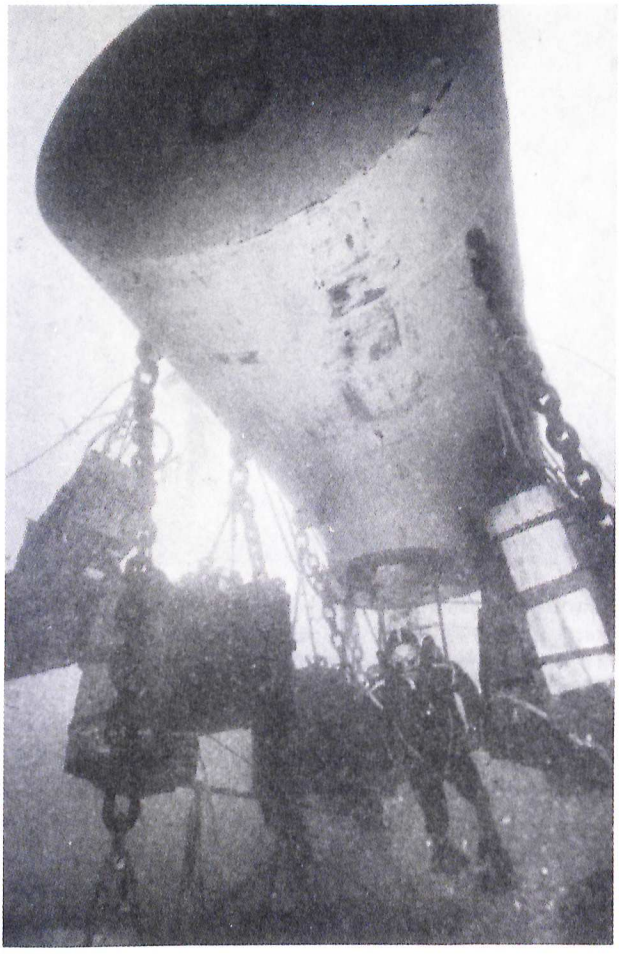

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Figure 3-5. Interior of The Conshelf I Habitat, Diogenes. *(Courtesy of The Cousteau Society, Inc., 930 West 21st Street, Norfolk, VA 23517, a membership-supported environmental organization.)*

simple grid network at a depth of 32.8 feet (10 m) and a second one at 82 feet (25 m). The grids established the limits of their diving excursions.

The two men took daily psychological tests, which included performing assembly tasks at a table in the water outside the habitat. Similar tasks were carried out in the habitat for 2 hours each night. According to Cousteau, "The most exhausting of all this work was the medical checks inside the house. They had a one hour a day medical check and it was far too much. We reduced it at the end of the experiment" (Cousteau, 1965). The decompression procedure, which was carried out on the seventh day, required the two aquanauts to breathe a mixture of 80% oxygen and 20% nitrogen for 3 hours in the habitat while still on the bottom. This period was followed by a symbolic rest at 10 feet (3 m), after which they surfaced without further decompression (Cousteau and Millet, 1969). As Cousteau said, "The experiment was ended and it was a complete success" (Cousteau, 1963, p. 183).

The overall objectives of Conshelf I, and for Conshelf II and III, which soon were to follow, were described by Chouteau, Cousteau, and Alinat (1966, p. 207):

1. To calculate and make a practical study of the "coefficient of the useful duration [defined as

$$\frac{\text{Length of immersion (thus of work)}}{\text{Length of immersion} + \text{Duration of journey to surface}}$$

of a dive.
2. To lay down the conditions for prolonged dives, in particular the nature of the respiratory mixtures to be used, and their drawbacks.
3. To show the absence of harmful effects, long and short term, of those saturation dives.

CONSHELF II, 1963

Nine months following his success with Conshelf I, after weeks of back-breaking toil, Cousteau was ready to establish a colony of five men on the seafloor. The date was June 15, 1963, and the site was the Red Sea near Shaab-Rumi (Roman Reef) about 25 miles (40 km) northeast of Port Sudan (Cousteau, 1964c).

Conshelf II was to deploy five men for 4 weeks on the seafloor at a depth of 36 feet (11 m) breathing air. Additionally, during this same period, two men were to live for 1 week at a depth of 90 feet (27.4 m). As well as using a larger crew, Conshelf II had other purposes: to increase seafloor time; to demonstrate the feasibility of assemblying livable, underwater dwellings; to show the possibility of using a variety of underwater tools; and to use a two-man, self-propelled deep sea submersible.

The director of the undersea station was 38-year-old Professor Raymond Vaissiere of the Oceanographic Museum of Monaco. The other four members of the team were Claude Wesly, the 30-year-old chief diver; 33-year-old André Folco, an industrial designer; Pierre Vannoni, 31, a former customs inspector; and the chef, Pierrot Guilbert, 43. The sixth member of the team was the mascot Claude, the first undersea parrot. A standby parrot, Armand, was kept on the surface but was not needed because of Claude's outstanding performance.

The main structure of Conshelf II was called Starfish House. It was 34 feet (10.4 m) at its widest point and consisted of a central section and four 4×8 feet ($1.2 \text{ m} \times 2.4 \text{ m}$) cylinders (Fig. 3-6). Starfish House contained sleeping quarters, a living and dining area, sanitary facilities, and a diving ready room. This arrangement was a significant advance over the spartan Conshelf I habitat. It rested on 7-foot long (2.1 m) telescopic legs, which allowed for leveling the structure on the seafloor. The habitat required 100 tons of ballast to attain the necessary negative buoyancy, which included 2000 lead pigs, each weighing 100 pounds (45.4 kg), that

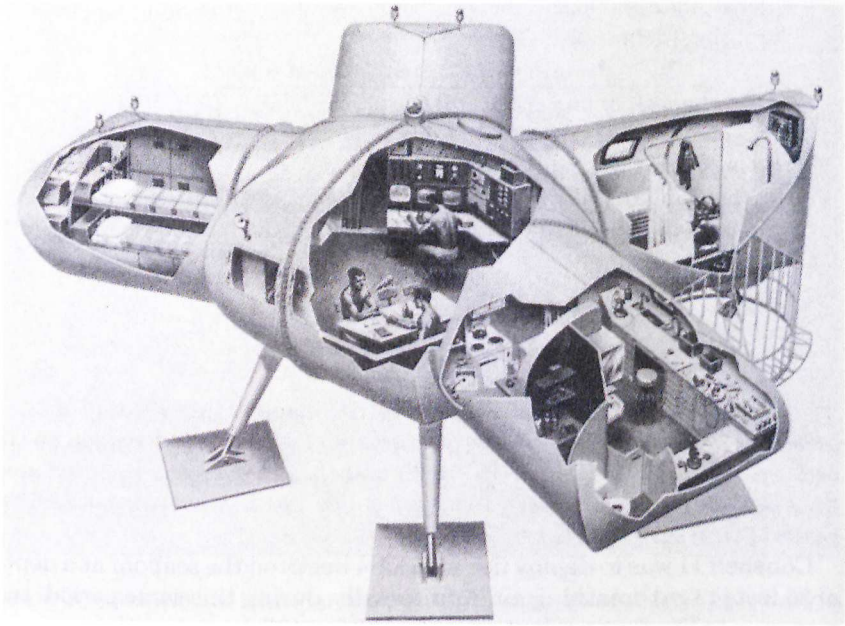

Figure 3-6. Conshelf II Habitat, Starfish House, (© *1964 National Geographic Society.*)

had to be handled by the divers. Temperature inside was maintained at 80°F (26.7°C) and humidity at 85%. Life-support functions were supplied by a surface ship.

In addition to Starfish House, Cousteau's colony included a habitat named Deep Cabin, stationed on a narrow ledge at a depth of 90 feet (27.4 m). It was a 7-foot-diameter (2.0 m) cylinder mounted on a tripod of telescopic legs and consisted of two vertical rooms (Fig. 3-7). The lower room contained diving gear, tools, and the open hatch to the sea. The upper room, used for living, contained two bunks, a kitchenette, an intercom, a phone, and a TV camera connected with the monitor in Starfish House. The aquanauts in Deep Cabin breathed a mixture of 50% helium and 50% air (Aquadro and Chouteau, 1967).

The narrow ledge on which Deep Cabin was placed proved to be a source of much difficulty during emplacement. The cylinder fell off several times once with the aquanauts inside, eventually special mooring cables and anchors were used to secure it.

Conshelf II included other interesting structures. One was an underwater hanger for the hydrojet diving saucer, a two-man submersible capable of diving to depths of 1000 feet (305 m) (Cousteau, 1964*b*). Air at the top

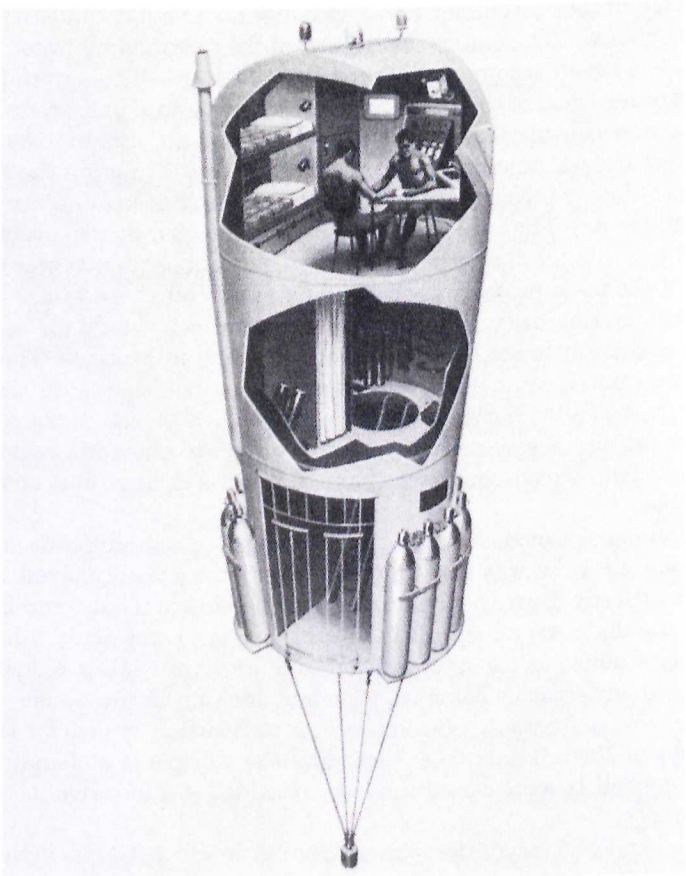

Figure 3-7. Conshelf II Habitat, Deep Cabin. *(Courtesy of The Cousteau Society, Inc., 930 West 21st Street, Norfolk, VA 23517, a membership-supported environmental organization.)*

of the hanger allowed the saucer to be lifted free of the water while still 36 feet (110 m) beneath the sea so that the crew could exit the saucer and conduct maintenance, battery recharging, and other activities independent of weather conditions on the surface. Air for the hanger came from the same support ship that supplied Starfish House. The other structure in the colony was a tool shed, open to the sea, used to store fish traps and other equipment.

Raymond Kientzy, 33, and André Portelatine, 46, stayed in Deep Cabin for a week, making many routine excursions to a depth of 165 feet (50.3 m) and three excursions to about 360 feet (110 m). They breathed com-

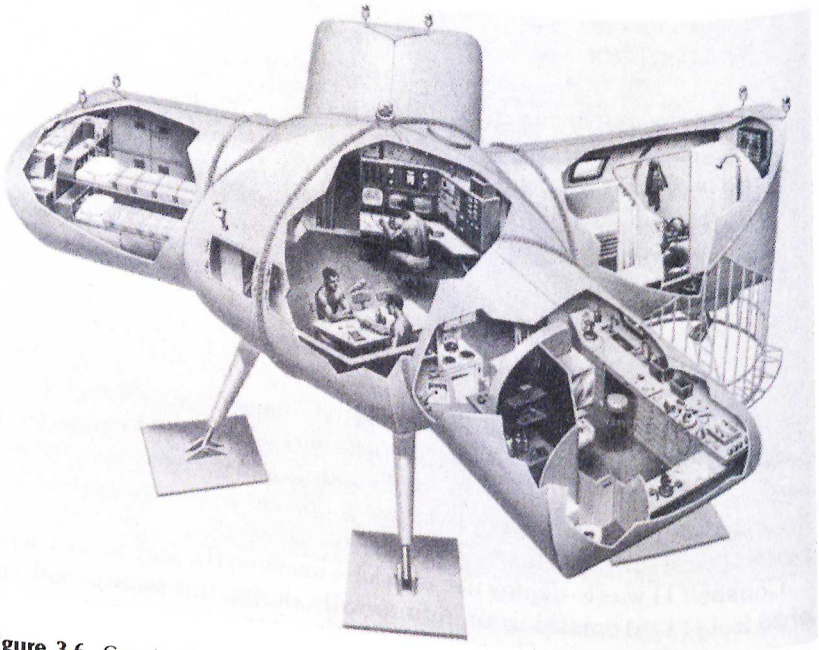

Figure 3-6. Conshelf II Habitat, Starfish House, (© *1964 National Geographic Society.*)

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In addition to Starfish House, Cousteau's colony included a habitat named Deep Cabin, stationed on a narrow ledge at a depth of 90 feet (27.4 m). It was a 7-foot-diameter (2.0 m) cylinder mounted on a tripod of telescopic legs and consisted of two vertical rooms (Fig. 3-7). The lower room contained diving gear, tools, and the open hatch to the sea. The upper room, used for living, contained two bunks, a kitchenette, an intercom, a phone, and a TV camera connected with the monitor in Starfish House. The aquanauts in Deep Cabin breathed a mixture of 50% helium and 50% air (Aquadro and Chouteau, 1967).

The narrow ledge on which Deep Cabin was placed proved to be a source of much difficulty during emplacement. The cylinder fell off several times once with the aquanauts inside, eventually special mooring cables and anchors were used to secure it.

Conshelf II included other interesting structures. One was an underwater hanger for the hydrojet diving saucer, a two-man submersible capable of diving to depths of 1000 feet (305 m) (Cousteau, 1964*b*). Air at the top

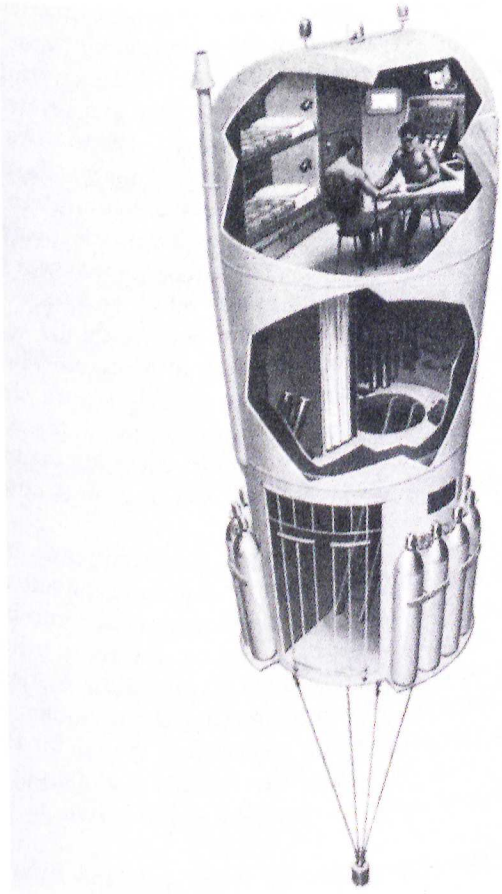
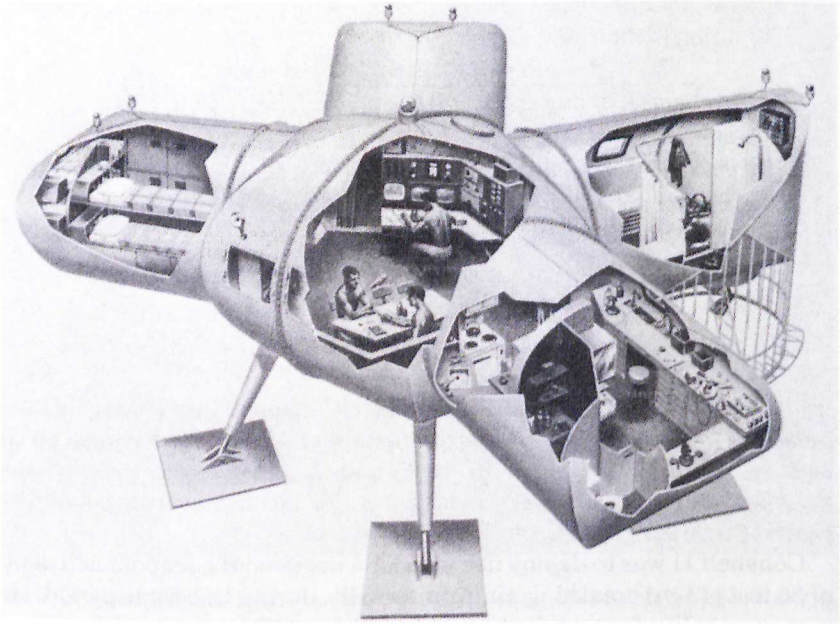


Figure 3-7. Conshelf II Habitat, Deep Cabin. *(Courtesy of The Cousteau Society, Inc., 930 West 21st Street, Norfolk, VA 23517, a membership-supported environmental organization.)*

of the hanger allowed the saucer to be lifted free of the water while still 36 feet (110 m) beneath the sea so that the crew could exit the saucer and conduct maintenance, battery recharging, and other activities independent of weather conditions on the surface. Air for the hanger came from the same support ship that supplied Starfish House. The other structure in the colony was a tool shed, open to the sea, used to store fish traps and other equipment.

Raymond Kientzy, 33, and André Portelatine, 46, stayed in Deep Cabin for a week, making many routine excursions to a depth of 165 feet (50.3 m) and three excursions to about 360 feet (110 m). They breathed com-



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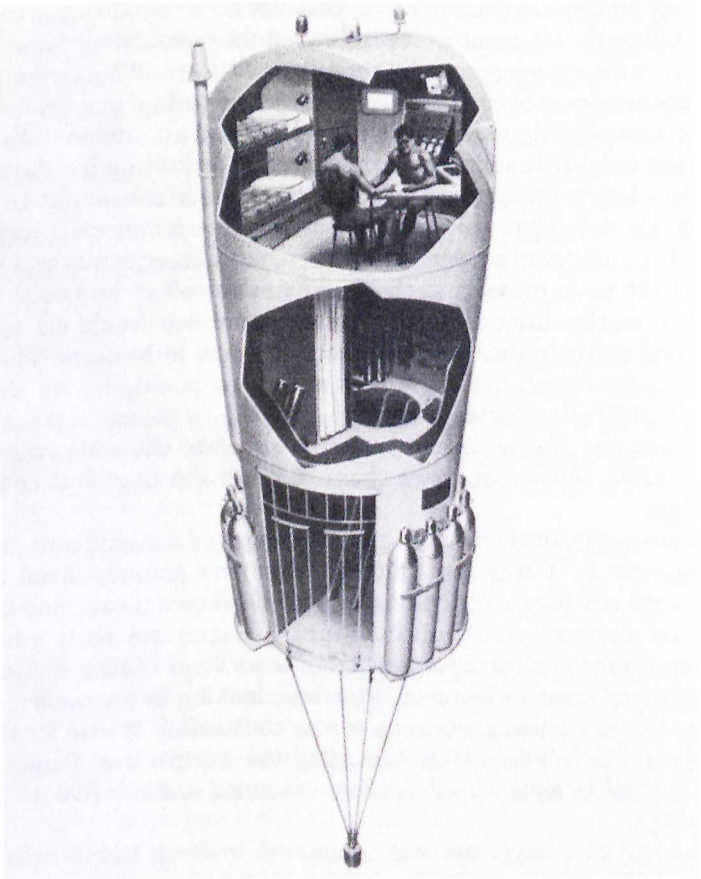

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pressed air for these excursion dives. Because no air conditioner was used in Deep Cabin, the temperature rose to that of the surrounding water—85°F (29.4°C)—with an accompanying humidity of 100%. This environment, plus the other rigors of this pioneering project, resulted in a severe loss of appetite and considerable sleeplessness (Cousteau, 1964*b*). As if the heat, pressure, and humidity were not enough, for the first few days, Deep Cabin kept losing pressure so that the water inside rose about 16 inches (40.6 cm) per day. The level continued to rise until it was discovered that the leak was through the television cable, which subsequently was sealed.

One of the main projects in the water was to collect and observe fish and other marine organisms. Collected specimens would be used for display and study in the Oceanographic Museum in Monaco. The aquanauts used fine-mesh nylon gill nets and traps positioned on the reefs to capture the fish unharmed. Some fish were then placed in transparent plastic bags and suspended in the water, much to the consternation of the larger fish, which could see them through the bags but could not get at them.

The four-week Conshelf II program represented a significant advance over Conshelf I. It was the first time humans actually lived on the seafloor with any degree of comfort, cooked their own meals, and became part of the undersea environment. Starfish House was truly a habitat, and Deep Cabin was the next version of a survival shelter. Conshelf II provided many creature comforts that were lacking in previous shelters. Madame Cousteau was a welcome visitor to Starfish House for the last four days of the mission, thus becoming the world's first female aquanaut. Conshelf II represented the first extended seafloor live-in, lasting a full month.

At the end of 7 days, the two aquanauts in Deep Cabin breathed a mixture of 50% oxygen and 50% nitrogen for 3.5 hours prior to returning to Starfish House, still resting safely at a depth of 36 feet (11 m). After remaining overnight in Starfish House, Kientzy and Portelatine, together with the three remaining members of the Starfish House crew, used the following decompression procedure prior to surfacing (Cousteau 1964*c*):

Time (minutes)	*Breathing Mixture*
15	80% O_2/20% N_2
15	air
30	80% O_2/20% N_2
30	air
60	80% O_2/20% N_2
Surfaced	

Two members of the Starfish House team and Madame Cousteau already had decompressed to make room for the Deep Cabin crew. The successful completion of the decompression signaled the end of Conshelf II.

The Deep Cabin experiment marked a further advance in undersea exploration, with five aquanauts spending 4 weeks at a depth of 36 feet (11 m) and two aquanauts spending a full week at 90 feet (27.4 m). The experiment also represented the longest open-sea saturation exposure to date. Cousteau felt that the main achievement of Conshelf II was the capability to operate a small submarine (DS-2) entirely from a submerged base for the first time. At Shaab Rumi, DS-2 performed safely and efficiently, unhampered by winds or waves, as often happened when Calypso launched or lifted her. Based on the bottom, the DS-2 was never immobilized by bad weather (Cousteau, 1964b).

Conshelf II did have problems, primarily associated with emplacement, ballasting, broken moorings, legs breaking off the habitat, and Deep Cabin's falls off the narrow shelf. But problems are to be expected with pioneering programs, and all programs must be prepared to cope with such accidents. Fortunately, no one was injured seriously during Conshelf II, and Cousteau was the first to admit that the hazards were great and exceeded only by the challenges.

MAN-IN-THE-SEA II, 1964

Conshelf I and II had demonstrated that humans could live underwater for long periods of time. Both projects, however, were conducted in relatively shallow water and did not extend human capability to work at significantly greater depths than could be obtained with surface diving techniques, with the exception of the short, deep excursions to 360 feet (110 m) from the 90 feet (27.4 m) Deep Cabin.

Link's Man-in-the-Sea II program was designed to extend living and working capability to a depth of 400 feet (122 m). While planning his new project, Link learned of studies conducted in Monaco in which mice had been pressurized successfully to 400 feet (122 m), then to 2000 feet (610 m), and finally to 3000 feet (915 m). Experiments also had been completed at the University of Pennsylvania where mice were exposed successfully to 4000 feet (1220 m) for 4 hours (MacInnis, Dickson, and Lambertsen, 1967).

Link was also aware that the U.S. Navy had conducted chamber experiments late in 1963 in which divers were exposed to a depth of 400 feet (122 m) for 24 hours without ill effects. With the success of these studies encouraging him, Link proceeded with plans for Man-in-the-Sea II. His timetable was delayed, however, when the U.S. Navy submarine *Thresher* sank on April 10, 1963, and Link became involved in the ensuing investigation. It was January 1964 before Link's *Sea Diver* could sail to Key West, Florida, to prepare for the 400-foot (122 m) Man-in-the-Sea II dive.

It had become apparent to Link during Man-in-the-Sea I that suspending a chamber over the side of a moving, rolling ship was dangerous and uncomfortable for divers and that the deep dive he was planning would require larger, more comfortable facilities. Link felt the basic requirements were such that a facility should provide warmth, shelter, easy entrance and exit, easy deployment, and transportability on the support ship. His solution was to build a collapsible seafloor shelter that could be deployed easily over the side of a ship, ballasted, and secured on the bottom (Fig. 3-8). The habitat, called SPID (submerged portable inflat-

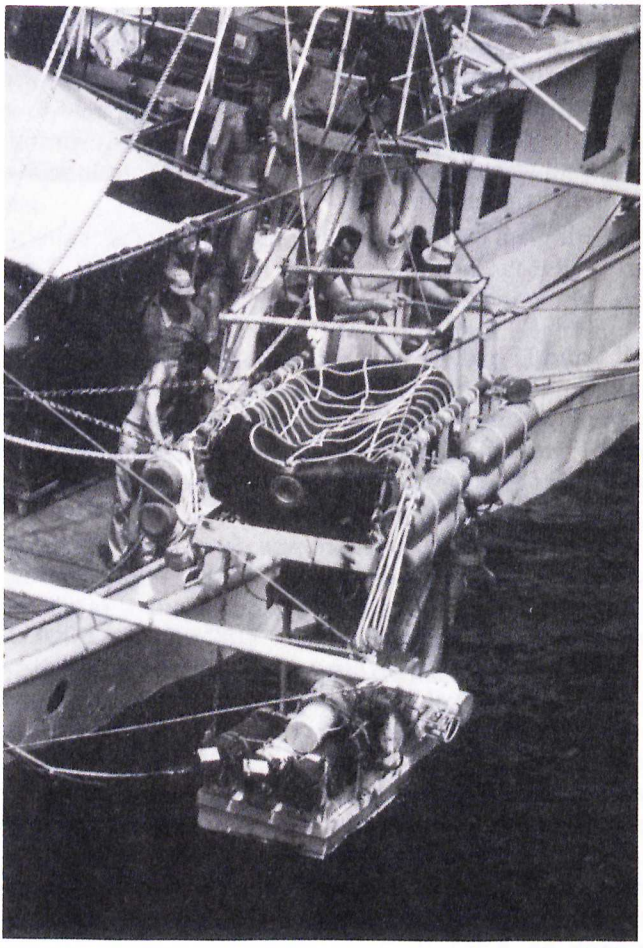

Figure 3-8. Preparing SPID for submersion. *(By Bates Littlehales; © 1965 National Geographic Society.)*

able dwelling), was an 8-foot (2.4 m) long by 4-foot (1.2 m) wide rubber bag mounted on a rigid steel frame.

Concurrently with the SPID design and manufacture, a second-pressure equalized flexible structure was designed and built (Link, 1966). Named IGLOO, this structure, although not a habitat, was designed to serve as a dry bottom environment for work on the seafloor. It could be ballasted for semipermanent bottom installation or attached to an anchor to be raised and lowered by an occupant. This inflatable workshop was operated for 50 days at 40-foot (12.2 m) depths.

As shown in Figures 3-8 and 3-9, the SPID frame was attached by chains to a ballast tray containing enough weight to keep secure on the

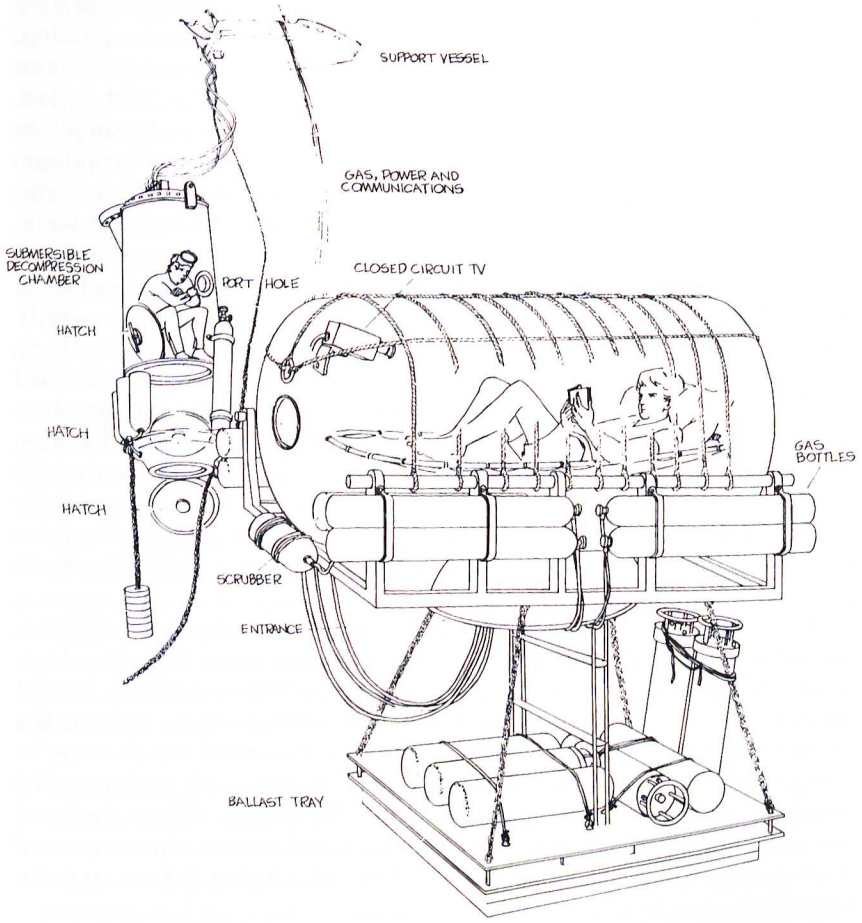

Figure 3-9. Artist's conception of Man-in-the-Sea II Habitat, SPID.

bottom when inflated. The ballast tray also served to hold watertight containers of supplies and equipment, such as food, water, tools, and underwater breathing equipment. The breathing mixture required for the dive was furnished through an umbilical hose from the surface. Additional emergency tanks of breathing gas were strapped to the middle of the habitat. Scrubbers were included in the habitat to remove CO_2 and analyzers incorporated to monitor oxygen levels.

Closed-circuit TV and a communication system were provided to monitor and talk to the aquanauts from the surface. In an effort to facilitate communication, seriously compromised because of the depth and high helium content in the breathing mixture, buzzers were placed at strategic locations for coded transmissions. An additional technique used to improve speech intelligibility was to have the aquanauts take a few breaths from auxiliary tanks containing air or air-helium mixture just prior to speaking. This technique produced a transient lung washout of part of the helium and, according to Dickson and MacInnis (1967, p. 95), "did in fact significantly improve voice intelligibility, and was extremely simple in execution." The diving system consisted of three major pieces of equipment: the SPID, used for sleeping, eating, and working; the submersible chamber used in the Man-in-the-Sea I experiments for transporting the aquanauts to and from the bottom; and a ship-mounted decompression chamber.

The SPID habitat was tested for more than a month on the seafloor in Key West in the spring of 1964. A dive site in the Bahamas subsequently was selected on the Northwest Providence Channel north of the Berry Islands. On the day of the dive, June 30, 1964, SPID was suspended under the surface from a boom off the starboard deck of the support ship. SPID also was connected by a coaxial cable and 600 feet (183 m) of hose carrying the breathing mixture of 3.6% oxygen, 5.6% nitrogen, and 90.8% helium. As SPID slowly submerged, the rubber bag inflated so that its internal gas pressure remained equal to or slightly greater than the ambient water pressure. Because there were no hatches on SPID, excess gas bubbled out through the open entrance collar.

Once SPID was secured on the bottom at a depth of 430 feet (131 m), the submersible decompression chamber was suspended from the ship's boom and lowered a few feet below the surface. The two divers, Robert Stenuit and Jon Lindbergh, then dove from the surface, entered the chamber at 9:45 A.M., secured the hatch and pressurized the chamber to a depth of 150 feet (46 m), and proceeded to check all systems. The breathing mixture was 23% oxygen and 77% helium. When they had determined that all systems were operating and secure, they increased the internal pressure to an equivalent depth of 200 feet (61 m), and the chamber began its descent.

Two hours and 15 minutes later, the two divers reached bottom and completed 45 minutes of pressurization (Stenuit, 1965). At this time,

the gauge pressure was read at 415 feet (126 m), and the breathing mixture changed to 3.6% oxygen, 5.6% nitrogen, and 90.8% helium. The divers then opened the hatch of the submersible chamber and swam to the SPID.

The submersible chamber remained near the SPID to be used both as the personnel transfer chamber and as a backup refuge on the bottom. It could be mated to the deck decompression chamber aboard the support ship, thus permitting the pressurized transfer of divers.

A number of problems developed at the outset, including heater failure, lights imploding, scrubber breakdown, and malfunction of the heated diving suits. The worst of the problems was the failure of the CO_2 removal system, which required Stenuit and Lindberg to leave SPID after only 30 minutes inside and return to the nearby cylinder. The repairs were made on the surface, and by 7:30 P.M. the aquanauts once again were inside SPID (Stenuit, 1965). The remaining problems were overcome, and the divers ultimately were able to perform simple tasks, such as observing and photographing local sea life. The water temperature at the saturation depth was approximately 72°F (22.2°C). Although the two aquanauts carried out repeated dives into the sea, the major problem during the exposure was their inability to maintain thermal equilibrium, the same problem that had plagued the subjects in Bond's Genesis experiments involving helium.

After 49 hours on the bottom, the divers reentered the submersible decompression chamber, secured the internal hatch, and were winched to the surface. While the divers were still under pressure, the submersible chamber was brought aboard and mated to the deck decompression chamber. After 92 hours of decompression, conducted at the rate of about 5 feet (1.5 m) per hour, the divers emerged from the chamber. During and following the 92-hour decompression, the divers repeatedly were examined by a physician. There was no evidence of clinical abnormalities resulting from the exposure, although signs and symptoms of mild decompression sickness in Stenuit were observed 25 feet (8 m) from the surface, the problems were resolved rapidly on return to increased ambient pressure and increased partial pressure of oxygen (Bennett and Elliott, 1975; Bornmann 1967). MacInnis (1966, p. 10) summarized the significance of this dive as follows:

> Their dive had shown that men could live and work effectively more than 400 feet below the surface for a substantial period, protected by an almost autonomous undersea dwelling, and be successfully recovered from such depths and decompressed on the surface at sea. More specifically, it demonstrated the flexibility and mobility of the three-chamber concept. It also emphasized some problems, including the voice distortion caused by helium and the need for a larger breathing-gas supply to support muscular

exertion. It showed that the control of humidity in an atmosphere in direct contact with the sea is extraordinarily difficult. The relative humidity in the chamber was close to 100 percent and both divers complained of softened skin and rashes. Temperature was a problem too. Both men preferred having the chamber temperature between 82 and 85 degrees F (28°C and 29.4°C). In the water, we realized, heated suits are required to keep divers comfortable even in the Caribbean Sea.

A detailed account of the physiological and engineering aspects of Man-in-the-Sea II can be found in Dickson and MacInnis (1967).

Important steps were made toward the development of recirculating breathing equipment and heated diving suits, and valuable insights were gained with respect to solving the problem of speech distortion in a helium environment. According to Link, the greatest problem yet to be solved was the handling of heavy gear from the deck of a support ship (Link, 1973). This was, and still is, one of the most difficult problems facing those working at sea.

SEALAB I, 1964

The Genesis laboratory experiments, the approval by the secretary of the navy to use human subjects in saturation diving experiments, Link's success, and Cousteau's pioneering programs in the Mediterranean and Red seas now emboldened the U.S. Navy to implement its own man-in-the-sea program. The purpose of this program was to advance scientific and practical understanding of human capabilities for living and working under the sea—specifically, to repeat and extend, under open sea conditions, the laboratory experiments designated as phase E of project Genesis. The site selected for this effort was approximately 26 miles (42 km) off Bermuda and located in 193 feet (58.8 m) of water at the base of a manmade tower named Argus Island.

The Sealab I habitat was constructed from two floats, made of ¾-inch (1.90 cm) steel welded together to form a cigar-shaped chamber 40 feet (12.2 m) long and 10 feet (3 m) in diameter (Fig. 3-10). Access to the sea was through two manholes in the bottom of the chamber. Two 12-inch (30.5 cm) portholes were installed on each side of the habitat. There were no closable hatches. End sections of the habitat were fitted to hold water ballast, which provided 20 tons of negative buoyancy, breathing gas for emergency use, and electrical equipment. Twenty-four feet (7.3 m) of living space in the center of the habitat was stuffed with bunks, lockers,

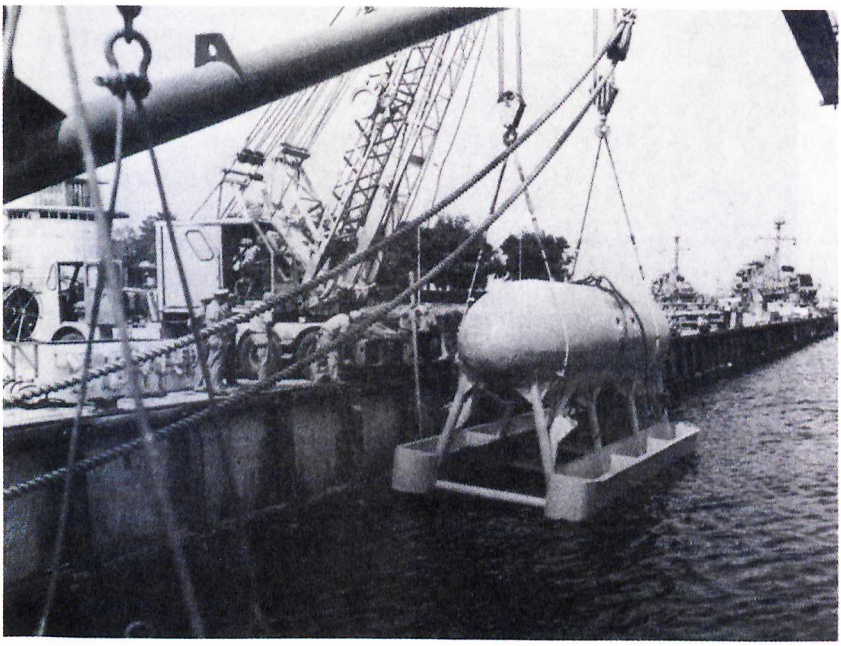

Figure 3-10. Sealab I Habitat. *(Official U.S. Navy Photograph.)*

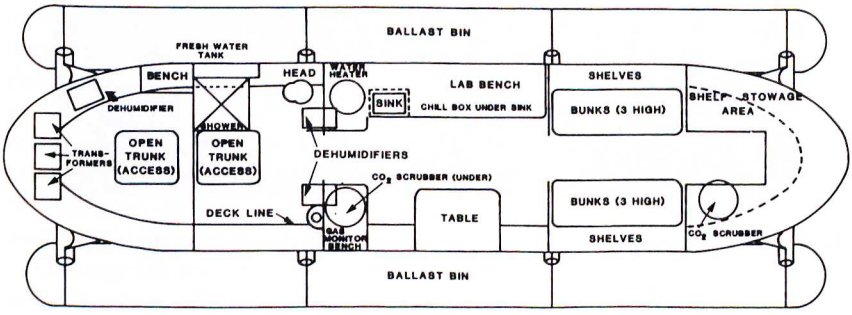

Figure 3-11. Plan View of the Sealab I Habitat. *(From H. O'Neal, G. Bond, R. Lanphear, and T. Odum, 1965, Project Sealab Summary Report, an Experimental Eleven-Day Undersea Saturation Dive at 193 Feet, ONR Report ACR-108, Office of Naval Research)*

laboratory equipment, environmental controls, refrigerator, a hot plate, an oven, a food locker, a shower, a toilet, air-conditioning equipment, storage space for scuba gear, and the aquanauts (Figs. 3-11, 3-12).

Attached to the habitat were various cables for electricity, compressed

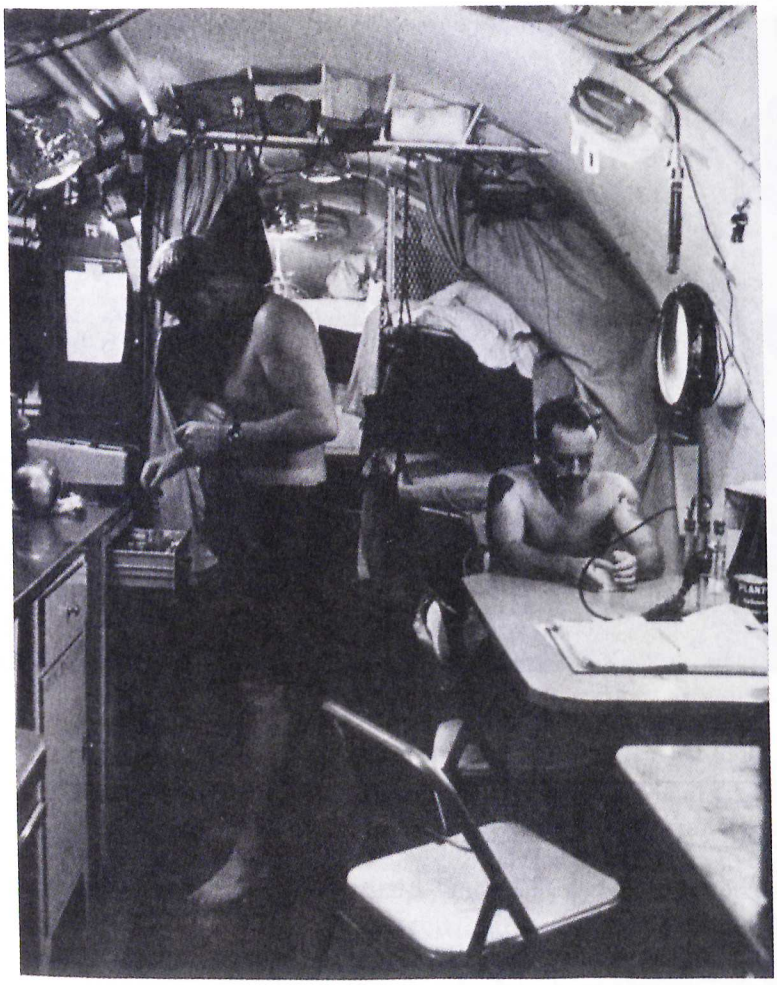

Figure 3-12. Interior of the Sealab I Habitat. *(Official U.S. Navy Photograph.)*

air and helium, fresh water, telephone, an electro-writer, an atmospheric sampling line, and a two-channel TV monitoring system. All of these cables terminated in the support ship, a 200-foot (61 m) navy Lighter.

The third major item of equipment was a submersible decompression chamber, which served as a pressurized elevator and a potential escape capsule in much the same manner as the chamber used in Man-in-the-Sea II.

Sealab I also had its share of technical problems. During open-sea

trials on May 20, 1964, the habitat flooded and sank in 60 feet (18.3 m) of water. It was refloated and towed to Panama City, Florida, for repairs. A week later, it was lowered successfully to the ocean floor and operated unoccupied for 30 hours. It was then towed to Argus Island where, after 5 days of unsuccessful attempts, it was placed on the seafloor at 1:30 P.M. on July 19, 1964, at a depth of 193 feet (58.8 m).

Occupancy began at 5:35 P.M. on July 20 when Gunner's Mate Lester E. Anderson left the submersible decompression chamber at a depth of 165 feet (50.3 m) and swam to the habitat. Inside, he began singing "O Sole Mio" in his chipmunk, helium voice. Within 5 minutes, Anderson was joined by three more aquanauts, Lt. Robert E. Thompson, the team physician, Chief Quartermaster Robert A. Barth, and Chief Hospitalman Sanders W. Manning. Barth and Manning had participated previously in the Genesis laboratory experiments.

The breathing gas inside Sealab I varied slightly throughout the mission but generally consisted of about 4% oxygen, 17% nitrogen, and 79% helium. Excursions from the habitat were made using U.S. Navy Mark VI semiclosed-circuit scuba or twin 90ft^3 (2.6 m^3) scuba cylinders using a mixture of 50% helium and 50% air. A comfortable temperature range in the habitat was found to be 83° to 86°F (28.3° to 30°C). As Link and Cousteau had found, humidity, which remained at about 90% most of the time, was a problem.

A number of tasks were carried out by the aquanauts in addition to conducting physiological studies on themselves and maintaining the habitat. These tasks included observing surrounding sealife, taking pictures, inspecting the legs of the nearby Argus Tower, testing shark-attracting devices, and making specific marine biological observations. One of the projects they performed was to determine their ability to observe the activity of the Star I, an experimental one-man submersible, during its landing on a simulated submarine hatch and to assist in these operations. Manning nearly lost his life while photographing this procedure when his gas supply accidently was cut off (U.S. Navy, 1968; Bond, 1968).

One significant difference between Sealab I and the programs of Link and Cousteau was the extensive medical monitoring supervised by Dr. George Bond, affectionately referred to as Pappa Topside. This program enabled topside personnel to monitor the health of the four aquanauts and to obtain data that would prove invaluable for future missions. Medical testing and monitoring included sampling of blood and urine, noting skin and body temperature, observing wound healing, and measuring pulmonary functioning.

Two important clinical observations were noted during the exposure. There was an apparent slowing of all gross physiological and motor

functions, as well as an ability to acclimatize to the body caloric loss in the gaseous and water environments. It also was noted that when oxygen levels were held at 4% or greater, the aquanauts reported an improved sense of well-being, a result attributed to the increased density of the breathing gas, which was about 1.6 times greater than sea-level air, causing an impaired pulmonary ventilation and a need for an increased molecular concentration of oxygen. Within the first 24 hours of exposure at 193 feet (58.8 m) after denitrogenation in the oxygen and helium atmosphere, exposure to compressed air resulted in an immediate and dangerous level of nitrogen narcosis, equivalent to that experienced breathing air at 350 feet (106.7 m). The authors concluded that once the body is essentially denitrogenated, susceptibility to nitrogen narcosis is significantly increased (Bennett and Elliott, 1975).

On Sealab I's eleventh day of successful operation, a decision was made to terminate the experiment because of a threatening tropical disturbance located about 700 miles (1167 km) to the south. Operational plans called for the aquanauts to ride the habitat to the surface with the habitat serving as their decompression chamber. As the habitat neared the surface, rough seas began affecting the chamber and putting a great strain on the Argus Island crane.

As a safety precaution, at 7:32 A.M. on July 31, the four aquanauts left the habitat at the 81 feet (24.7 m) depth and swam into the submersible decompression chamber (SDC). At 2:40 P.M. the SDC was raised to the cargo deck of Argus Island and placed in a horizontal position where the decompression period of 56 hours was completed at an average rate of about 3.5 feet (1.1 m) per hour (O'Neal et al., 1965).

Analysis of the information gathered during Sealab I showed some major problem areas: better engineering needed for lowering and raising; lower humidity; helium speech unscrambling; umbilical reliability; communications; swimmer navigation equipment; reliability of equipment in the helium-oxygen atmosphere; and some way to reduce the amount of gear the swimmer has to use and store in the habitat.

Nevertheless Sealab I was a major success. Never before had humans worked and lived in the sea at so great a depth for so long. Although cut short by the impending hurricane, the experiment gathered a valuable store of physiological data both from instruments and personal experiences. Much was learned about the open-sea management of habitat programs that was to benefit future navy programs and lay the groundwork for Sealab II, soon to follow. The conclusions and recommendations of the navy resulting from Sealab I are summarized in Table 3-1.

After sitting idle at a navy dock for several years in Panama City, Florida, Sealab I was abandoned to a water grave in 1974, where it

Table 3-1. Summary of Conclusions and Recommendations of Sealab I

Conclusions	*Recommendations*
A. Human subjects can live and work under pressure at 193 feet (58.8 m) in the open ocean without significant physiological or psychological problems.	A. Major changes in habitat design and/or handling procedures must be initiated for future Sealab work.
B. All major systems used in Sealab I worked in a fashion adequate for life support.	B. A higher degree of independence from surface support must be achieved. A smaller, permanently attached umbilical cord must be provided. Specific items which must be improved are: Gas supply Gas control and monitoring Power (at least for emergencies) Communications
C. The major mechanical problems, encountered in raising and lowering the habitat, were caused by surge of the habitat and surface ship. These problems were most serious from the surface to 100-feet (30.5 m). A major engineering effort is required for solution of this problem.	C. As Sealab crews enlarge, at least one man must be assigned full time to housekeeping and equipment maintenance.
D. This concept offers a step toward increased efficiency in the utilization of human diver's time over existing techniques. Although, in this experiment, four to five hours outside working time was the maximum experienced, it appears that six hours outside work per man in each 24-hour period is practicable. The major losses of working time in this experiment were caused by inadequate preparation for housekeeping functions, and lack of adequate work schedules. Some working time was lost during the subjects' acclimatization period.	D. For further experiments, a major effort must be made in improvement of housekeeping (material and organization), and in time-and-motion studies and layout of work schedules.
E. Techniques for largely overcoming the helium speech problem were demonstrated. However, fully satisfactory equipment is not yet in hand.	E. Vehicles for swimmer transport must be provided. A usable one-man wet vehicle is now available; a two-man wet vehicle is anticipated. Consideration must be given to a dry vehicle with lock-in, lock-out capability to permit greater excursions in depth.
	F. Physiological studies must be performed to determine the permissible time of depth excursions from saturation level under no decompression and under programmed decompression limits.

(continued)

Table 3-1. *(continued)*

Conclusions	*Recommendations*
F. Provision for adequate body heating while swimming remains a major problem. Although this experiment was conducted in 69°F (20.6°C) water, to which the subjects acclimatized to a significant degree, lack of heating for swimming imposed restraints on the subjects during excursions.	
G. The submersible decompression chamber performed adequately for the purposes of this operation, but difficulty of handling it points up the desirability of a more compact unit which can be married to a larger surface chamber.	

Source: Based on information in O'Neal, H., G. Bond, R. Lanphear, and T. Odum, 1965, *Project Sealab Summary Report, An Experimental Eleven-Day Undersea Saturation Dive at 193 Feet,* Office of Naval Research, ONR Report, ACR-108, Washington, D.C.

remained until it was salvaged in 1981. It has now been cleaned and refitted for public display at the country's first diving museum in Panama City, Florida.

CONCLUSION

We have seen what must be viewed historically as a rapid transition from the laboratory experiments of Genesis to the first open-sea saturation diving programs of Link, Cousteau, and the U.S. Navy. The period from September 1962 to July 1964 was indeed significant. In less than 2 years, humans had moved to the seafloor to live for a month at 33 feet (10 m), 2 days at 430 feet (131.1 m), and 11 days at 193 feet (58.8 m). Table 3-2 summarizes the pioneering efforts from 1962 through 1964 that demonstrated the feasibility of saturation diving.

Although a few relatively simple tasks were carried out by these pioneer aquanauts, the projects were designed primarily to test humans and equipment. The habitats, with perhaps the exception of Starfish House, really were seafloor survival shelters with few frills and many problems. The groundwork was laid, however, for the next series of programs where performance of work and scientific tasks were primary goals.

Table 3-2. Development of Saturation Diving, 1962–1964

Date	*Sponsor*	*Project Name*	*Depth (Feet)*	*Duration*	*Location*	*Dwelling Type (Size in Feet)*	*Divers Aquanauts*	*Breathing Gas (%)*
Aug. 1962	Link	Trial Link	60	8 hrs.	Mediterranean Sea	3 × 11 Cylinder	Link	10.0 O_2 3.0 N_2 87.0 He
Sept. 1962	Link	Man-in-Sea I	200	2 hrs.	Villefranche Mediterranean Sea	3 × 11 Cylinder	Stenuit	3.0 O_2 97.0 He
Sept. 1962	OFRS, France	Conshelf I	35	7 days	Marseilles Mediterranean Sea	8 × 16 Cylinder	Falco, Wesly	Air
Nov. 1962	U.S. Navy	Genesis C	Surface	6 days	NMRL[a]	9 × 15 dry chamber	Barth Bull Fisher	21.6 O_2 4.0 N_2 74.4 He
April 1963	U.S. Navy	Genesis D	100	6 days	EDU[b]	6 × 12 dry chamber	Barth, Lavoie, Manning	7.0 O_2 7.0 N_2 86.0 He
July 1963	OFRS, France	Conshelf II	36	1 month	Shaab-Rumi Reef, Red Sea	four 4 × 8 cylinders in star configuration	Falco, Guilbert Vaissiere, Vanoni, Wesly	Air
July 1963	OFRS, France	Conshelf II	90	7 days	Shaab-Rumi Reef, Red Sea	7.5 × 16 cylinder	Kientzy, Portelatine	50.0 Air 50.0 He
Aug. 1963	U.S. Navy	Genesis E	198	12 days	NMRL[a]	9 × 15 dry chamber	Barth, Bull, Manning	3.9 O_2 6.5 N_2 89.6 He

(continued)

TABLE 3-2. *(continued)*

Date	*Sponsor*	*Project Name*	*Depth (Feet)*	*Duration*	*Location*	*Dwelling Type (Size in Feet)*	*Divers Aquanauts*	*Breathing Gas (')*
Dec. 1963	U.S. Navy		300	24 hrs.	EDU[b]	6 × 12 dry chamber	Kosimaki Simeone	O_2 He
Feb. 1964	U.S. Navy		300	24 hrs.	EDU[b]	6 × 12 dry chamber	2 divers	O_2 He
March 1964	U.S. Navy		400	24 hrs.	EDU[b] dry chamber	6 × 12	Kennedy, Zuber	O_2 He
June 1964	Link	Man-in-Sea II	432	48 hrs.	Great Stirrup Cay, Bahamas	3.9 × 7.9 rubber cylinder	Lindbergh, Stenuit	4.0 O_2 96.0 He
July 1964	U.S. Navy	Sea Lab I	193	11 days	Argus Island, Bermuda	9 × 40 cylinder	Anderson, Barth, Manning, Thompson	4.0 O_2 17.0 N_2 79.0 He

[a] Naval Submarine Medical Research Laboratory, New London, Conn.
[b] U.S. Navy Experimental Diving Unit, Washington, D.C.

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Chapter 4

Working on the Seafloor

The pioneering undersea programs demonstrated that humans could survive and live on the ocean floor continuously for several weeks. After thousands of years of dreaming, the possibility of virtually unlimited bottom time was real. Although such programs received much publicity and excited the imaginations of many, still to come was the application of the hard-won knowledge to the development of the continental shelf, to the advancement of science, and to important defense requirements.

Although aquanauts had been provided with what essentially were survival shelters, we had yet to define the work that could be best accomplished while living on the seafloor, as well as to refine the facilities needed to support that work. The U.S. Navy, for example, had salvage, rescue, and other navy-related work to do and was determined at the time to build an undersea habitat designed for such purposes. In addition, scientists and recreational divers began to initiate underwater projects using saturation diving to carry out oceanographic and marine biological projects, as well as simple exploratory ventures.

The commercial diving industry quickly became aware of the potential application of saturation diving to the increasing requirements for working deeper and longer in the offshore oil and gas fields. It became apparent immediately, however, that although the concept of saturation diving provided the solution to the need for long work periods at consider-

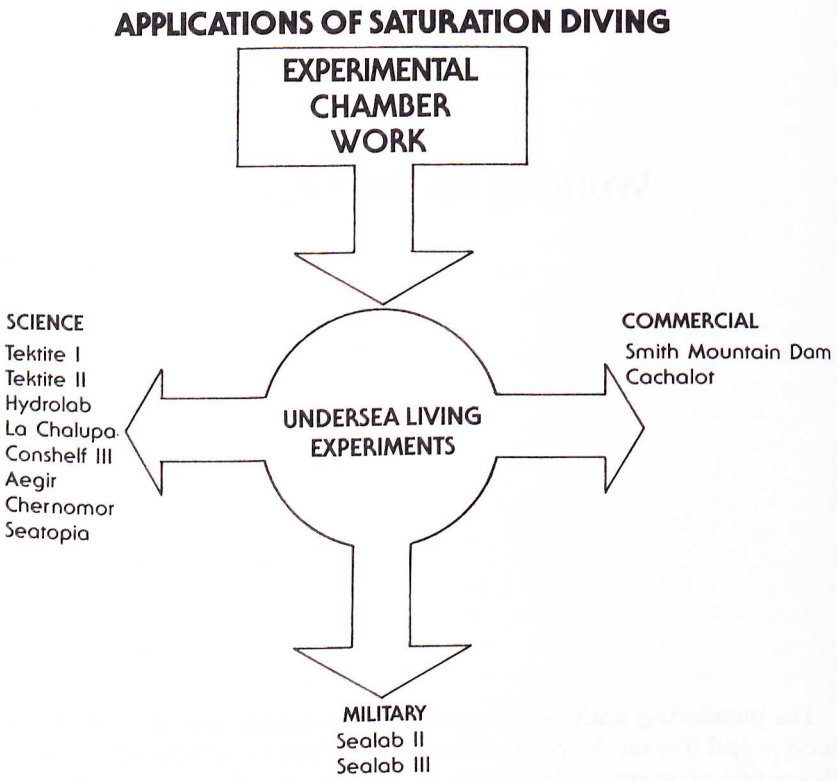

Figure 4-1. Applications of saturation diving.

able depths, the use of seafloor habitats was not the best approach for the offshore diving industry. Accordingly, techniques were developed to allow working commercial divers to live in a pressurized chamber on a surface platform and travel to and from the seafloor in a pressurized personnel transfer chamber. The rather marked diversification of application of saturation diving beginning in 1965 is depicted in Figure 4-1.

The habitat programs described in this chapter represent the major efforts since 1965 to extend the capability to live and work on the seafloor for scientific or exploratory purposes.

SEALAB II, 1965

Building on the success of Sealab I, the U.S. Navy initiated a saturation diving project that became known as Sealab II. In January, 1965, a

goal was set to place aquanauts on the ocean floor by August 20. The goal was missed by only 8 days. During those months, a habitat was built, a surface-support vessel modified, a decompression complex designed and fabricated, and the aquanauts trained.

Sealab II involved the design and engineering of equipment using new techniques and materials. Instead of the clear, warm water and hard bottom of Bermuda (Sealab I), Sealab II was placed in an environment more representative of the continental shelf surrounding the United States (Pauli and Clapper, 1967). The site selected was about a quarter of a mile off the end of the pier of Scripps Oceanographic Institution in La Jolla, California, at a depth of 205 feet (62.5 m). The major objectives of Sealab II were (1) determination of general human ability to do useful work at a depth of 205 feet (62.5 m) in a realistic ocean environment under saturated diving conditions, (2) measurement of physiological changes in humans as a result of extended diving, (3) assessment of stressful conditions and their effects on the group interactions of the aquanauts, (4) testing and evaluation of new equipment.

The extensive physiological and medical testing program established for Sealab II was based on areas of human physiology that previous experiments had indicated would be most susceptible to change under the conditions to which the aquanauts were to be exposed. Areas of study included were inert gas uptake and elimination; oxygen toxicity; respiration; hematology and blood chemistry; urine analysis; electrocardiography; electroencephalography; daily vital signs; and pulse, temperature, and blood pressure. Other studies included were exercise tolerance, effect of cold water on diver performance, radioisotope-tagged iron for plasma turnover and erythropoiesis (Mazzone, 1966).

One of the more extensive research programs of Sealab II was the human performance studies (Miller, 1966*b*) designed to study the broader aspects of adaptation to life and work in a hostile environment and to determine how well humans could perform specific scientific or operational tasks. The studies involved predive and postdive interviews and psychological tests, as well as tests conducted during the entire seafloor program. Tests included measures of visual, auditory, and psychomotor skills, observation and measures of performance during the in-water experiments, and psychological studies of group behavior inside the habitat (described in detail in (Pauli and Clapper, 1967; Radloff and Helmreich, 1968).

The design of Sealab II took advantage of the many lessons learned from Sealab I. Sealab II was a cylinder, 57 feet (17.5 m) long and 12 feet (3.6 m) in diameter, with capped ends and a small conning tower, which made it resemble a railroad tank car without wheels (Fig. 4-2). It was divided into four areas (Fig. 4-3). The entry area contained the main hatch

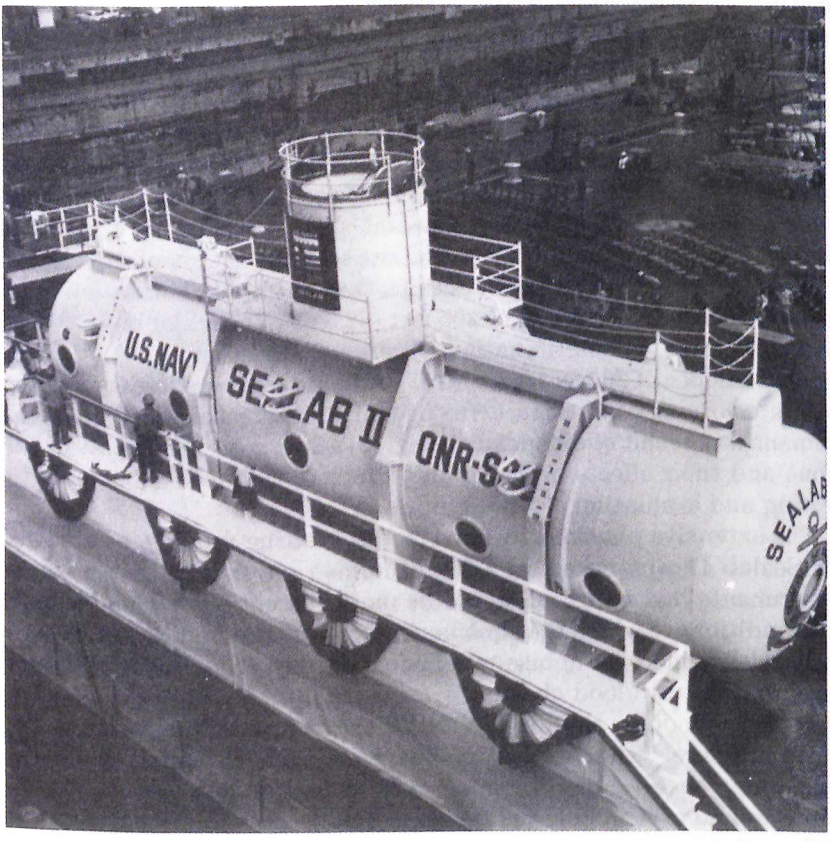

Figure 4-2. Exterior view of the Sealab II habitat. (*U.S. Navy Official photograph.*)

in the deck, two shower stalls, and swim gear stowage; a laboratory area, which included communication, test, and gas monitoring equipment and work space; and a general living area containing five double bunks, lockers, a folding table, and the galley.

The main entry hatch was located in an 8 × 8 foot (2.4 × 2.4 m) trunk extending 2.5 feet (75 cm) below the hull bottom surrounded by a shark cage. In addition, there were two 27-inch (69 cm) hatches for upper access and emergency escape. Eleven 24-inch (61 cm) viewing ports permitted ready observation of the sea. Ballast was provided both by the cement floor, into which heating cables had been imbedded, and variable-ballast water tanks in the overhead. Compared to Sealab I, the Sealab II habitat was luxurious. The aquanauts enjoyed a lavatory, sinks, a water heater, a

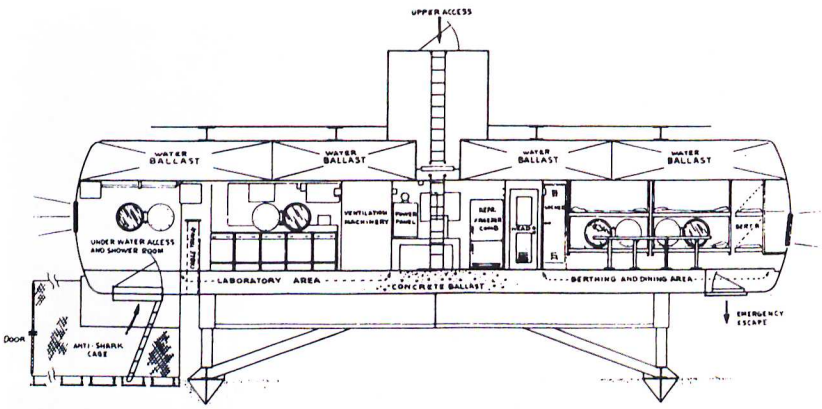

Figure 4-3. Side view of the interior of Sealab II habitat. (*From D. Pauli and G. Clapper, 1967, An Experimental 45-Day Undersea Saturation Dive at 205 Feet, Project Sealab Report, ONR Report ACR-124, Office of Naval Research, Washington, D.C.*)

toilet, showers, a refrigerator with freezer, and a good air-conditioning system.

One of the major problems in Sealab I had been an inadequate surface-support ship. For Sealab II a staging vessel used in Polaris missile tests was obtained. This vessel actually was two barges, each 110 feet (33.5 m) long and 34 feet (10.4 m) wide, spaced 22 feet (6.7 m) apart and connected by a covered structure to form a U shape (Fig. 4-4.) Facilities in this craft included a galley, dining and storage spaces, electric power generators, winches, air compressors, a 50-ton crane, a command center, and a ten-man deck decompression chamber (DDC), which allowed ten aquanauts to be brought to the surface in a pressurized personnel transfer capsule (PTC) designed to mate with the DDC (Fig. 4-5).

The habitat arrived at the site on August 21, 1965. On August 26, emplacement of the habitat was accomplished by flooding ballast tanks and employing a system of counterweights. On the bottom, electrical power and water were furnished through lines from the Scripps Institution pier. An umbilical cable from the support ship carried breathing gas, communications and instrumentation lines, and a secondary source of electrical power.

During descent, the habitat was held at a depth of 60 feet (18.3 m) for inspection and was found to be leaking helium gas. To minimize gas loss, lowering was continued to the bottom. Possibly due to this haste, the habitat settled with a 6° list to port and a trim to the stern of 6°. Aquanauts subsequently dubbed Sealab II "the Tilton Hilton."

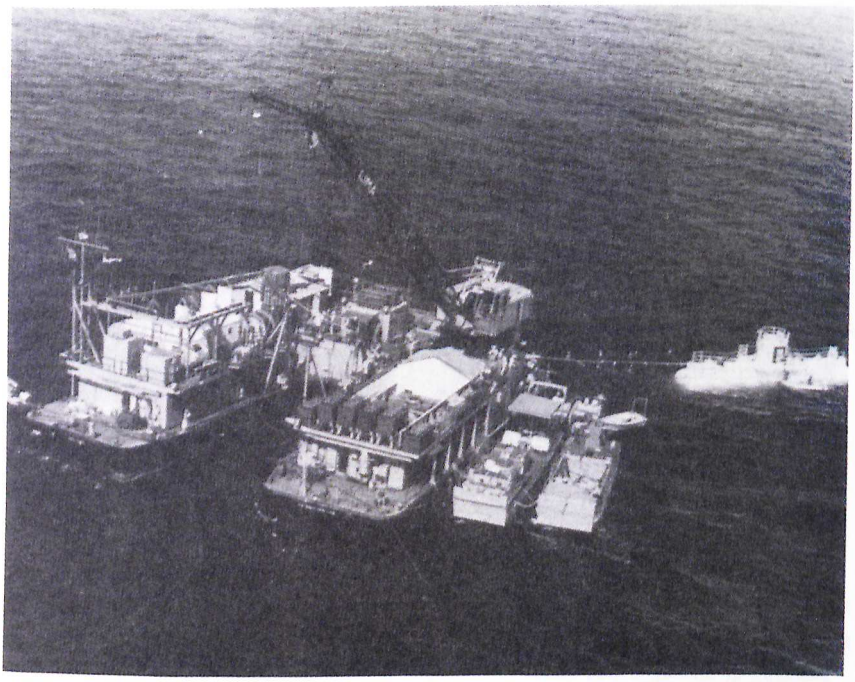

Figure 4-4. Sealab II support vessel Berkone. (*Official U.S. Navy photograph.*)

Two days later, the first team of ten aquanauts prepared to swim down to their new ocean-floor home. Two men went down first to open and inspect the habitat. Two more checked out the PTC, which rested on the bottom within 20 feet (6.1 m) of the main hatch. When the satisfactory condition of the two main structures was reported to topside, the remaining three two-man teams swam down to join the others.

On the first day, as part of the public relations program, a radio link was established with the Gemini space capsule in orbit 106 to 217 miles (170.5 to 349.1 km) above the earth. Astronaut-aquanaut Scott Carpenter, the Sealab II team leader, spoke to Astronaut Gordon Cooper in the space ship, the first conversation from sea bottom to outer space.

Once the seafloor chamber was reasonably habitable, the aquanauts devoted most of their efforts to scientific programs and equipment evaluation, including tests of mental and psychomotor ability, population dynamics of fish and other marine organisms, and geological studies. Sealab II clearly was the most sophisticated scientific and technical undersea program yet attempted.

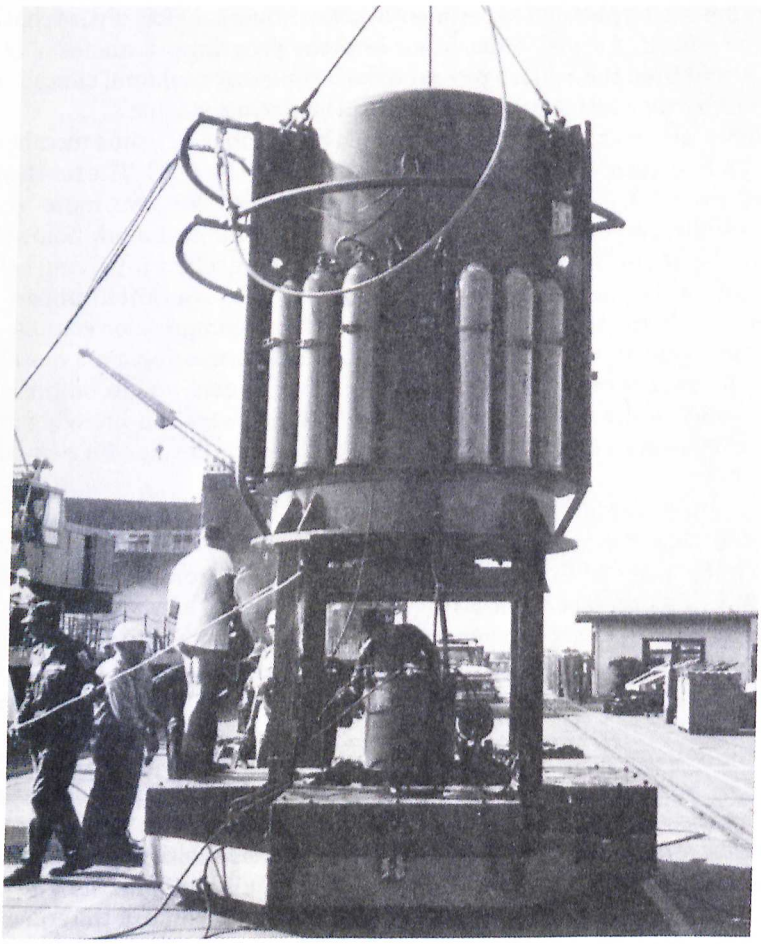

Figure 4-5. Sealab II pressurized personnel transfer capsule. (*Official U.S. Navy photograph.*)

Sealab II aquanauts were saturated at a depth of 205 feet (62.5 m). The life-support system provided a breathing mixture of 4% oxygen, 85% helium, and 11% nitrogen (Pauli and Clapper, 1967). Lithium hydroxide was used to remove carbon dioxide from the air, and charcoal was employed to remove odors. For reasons of safety, ascending excursions were not permitted to more than 30 feet (9.1 m) above the saturation depth.

A typical day in Sealab II involved about 20 hours of work. A substantial amount of this time was spent in preparation for dives, repair of

equipment, and general logistics. Although every effort was made to carry out all the planned experiments, these housekeeping duties continually interfered. As with most other seafloor programs, transfer of material to and from the surface proved to be a constant problem, complicated further by the clutter usually found in the diving station.

On the sixteenth day of the operation (September 12), nine members of the ten-man team were brought to the surface in the PTC. The tenth man, teamleader Carpenter, remained on the seafloor for two more weeks. Meanwhile, two members of team 2 entered the habitat a few hours prior to the departure of team 1 to obtain data on themselves involving helium uptake by the blood and tissues. Once the PTC was lifted aboard the support ship *Berkone,* and mated to the DDC, decompression commenced. For this team as well as for teams 2 and 3, decompression time was about 30 hours, at the rate of 6 feet (1.8 m) per hour. In general, decompressions went smoothly; extensive physiological studies were conducted, particularly for teams 2 and 3. Team 1 completed decompression on September 14, 1965.

During their fourteen days on the bottom, team 2 conducted numerous marine scientific experiments and tests of various equipment, including hot water suits and current meters. The one nonhuman member of the team was a porpoise named Tuffy (Fig. 4-6), who was used on an experimental basis to carry messages and perform tasks such as delivering tools from station to station in response to a buzzer or click. On one occasion, Tuffy delivered a small bag of fish (unopened) to the habitat for the aquanauts.

A nonscheduled event was the appearance of wild sea lions in the entrance trunk. They soon became friendly. They could breathe the compressed air in the habitat and then surface with no apparent ill effects. One of the sea lions, Sam (later reidentified as Samantha), quickly learned to respond to some of the same signals as Tuffy. She became a team pet and was quite affectionate with some of the aquanauts.

September 26 saw the departure of team 2 from the habitat and entrance of team 3. In addition to carrying out the now-routine medical and psychological tests, this team conducted a series of studies related to salvage and commercial diving. These tests included the use of special foam in raising the body of a downed aircraft, the use of a collapsible salvage pontoon, and the use of velocity power tools and pneumatic-power, zero-reaction hand tools.

On October 1 another communications first occurred. Aquanauts Richard Grigg and Robert Sheats spoke to oceanauts Cousteau and Lebon living on the floor of the Mediterranean Sea off the coast of Cap Ferrat during Cousteau's Conshelf III program.

Team 3 completed its mission on October 10 and finished decompres-

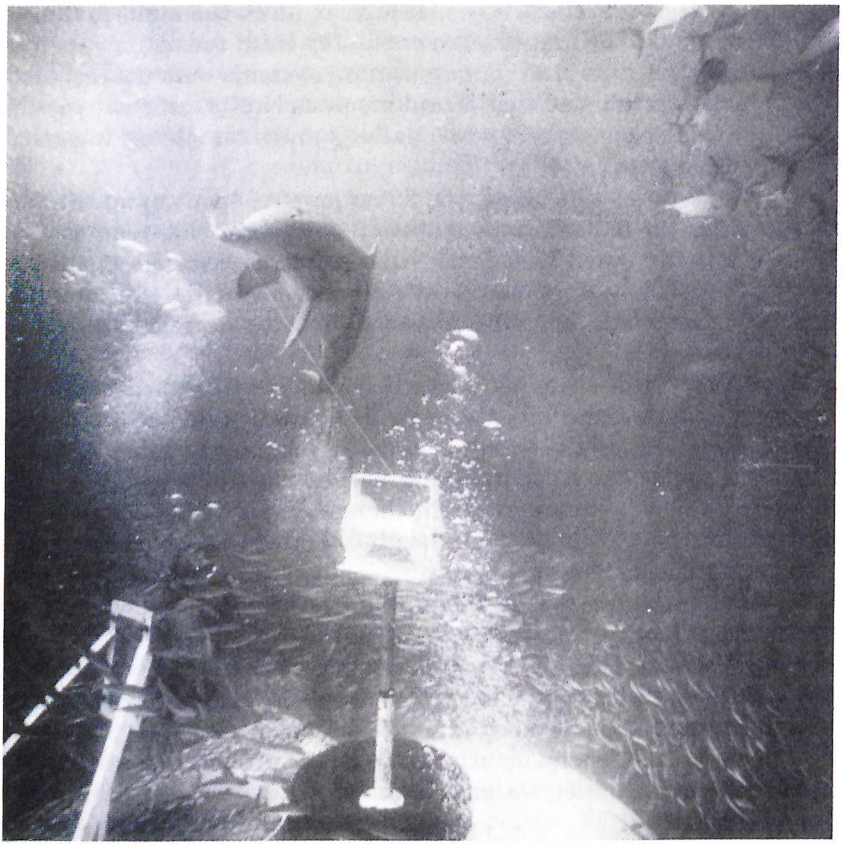

Figure 4-6. Tuffy at work during Sealab II. (*Official U.S. Navy photograph.*)

sion on October 12. The Sealab II habitat was raised to the surface on October 11 and towed back to Long Beach, California.

Low water temperature and poor visibility made Sealab II a more severe challenge to the individual aquanaut than had earlier habitat efforts. Its program required long hours of preparation and often was interrupted, delayed, or revised. Life in the Sealab II habitat was highly stressful due to lack of sleep, high relative humidity, and communication difficulties caused by the helium environment. Headaches, apparently caused by atmospheric contaminants, and bacterial ear infections, partly resulting from the high humidity and buildup of perspiration under the hoods worn by the divers, were the most frequent medical problems. Hair dryers and an alcohol-acetic acid mixture were used to dry the ears in an

effort to reduce infections. These measures reduced the number of infections from nine in the first team to one in the third team.

Swimmer navigation and communication systems were unacceptable. The program also showed that an autonomous habitat was not possible without a reliable underwater power package and a completely integrated life-support system.

In spite of these difficulties, the 28 aquanauts spent more than 450 man-days on the seafloor and conducted more than 400 man-hours of useful work in the water. They demonstrated that divers could be protected against the cold for several hours with the use of heated diving suits and that rather sophisticated salvage tasks could be accomplished under adverse conditions.

Postdive medical examinations revealed no neurological alterations resulting from the exposure, although EEG studies showed slight transient changes during the time at depth. Psychophysiological examinations also revealed no deleterious effects from the prolonged dive.

Although there were several slight changes in physiological functions, none was considered significant enough to limit future exposures under similar conditions. Some changes, such as body temperature, red blood cell count, and serum enzymes, indicated that further studies would be required to identify the etiology and pathophysiology. The principal investigators concluded, "In a Sealab type of exposure, general stress from multiple sources is the most consistent physiological deviant and that its impact is most severe during the first 5 days. This may indicate a need to condition the aquanaut prior to an operation in order to ensure peak performance during the critical period" (Bennett and Elliott, 1975, p. 514).

The achievements far outweighed the problems, however. Sealab II clearly was a major step forward in human occupation of the seafloor. While formal recommendations were not cited by Link or Cousteau, those resulting from Sealab II, as given in the following list (Pauli and Clapper 1967) reflect the findings of previous programs, as well as frustrations encountered before and since Sealab II.

Add more storage racks, hooks, etc. for external wet storage
Provide additional space for internal storage, maintenance, and set-up of diving equipment
Conduct research to determine the human comfort zone in Sealab-type atmospheres
Insulate all inside surfaces to prevent condensation
Reduce noise within the habitat to a minimum
Improve photographic conditions by installing photographic lights
Modify the decompression complex to allow handling and mating in higher sea states

Provide improved leveling techniques to compensate for uneven seafloor
Re-evaluate ballast, flood and blow systems
Provide the capability of over-pressurizing the habitat on the bottom to ensure adequate port and hatch sealing prior to raising
Redesign the diver entry hatch to facilitate entry
Modify transfer pot system to keep entry trunk unobstructed during transfer
Provide special viewing ports and investigate feasibility of bubble-type observation ports
Provide a large port near the entry hatch so that swimmers can be observed
Include hinges on outer port covers
Re-evaluate the entire habitat layout

SEALAB III, 1969

With the success of Sealab I and II, the navy now prepared for a third program, confident that seafloor living offered new and important vistas for science and engineering. Now the question was what could best be accomplished from the seafloor. To answer this question, the navy established an ocean engineering test range off San Clemente Island, California, where environmental tests and evaluation of deep submergence, ocean engineering vehicles, equipment, and technology were to be carried out from a habitat.

The Sealab II support ship, *Berkone,* was replaced with a larger ship, the *U.S.S. Elk River,* converted especially for Sealab III as well as serving as a general test-range support ship. It was configured to provide a stable working platform 225 feet (68.6 m) long. It held a 65-ton gantry crane, two DDCs, two PTCs, and a center well for lowering equipment into the sea. Also on deck were two vans, one a command center and the other a medical monitoring facility.

In pursuit of the overall questions of what underwater jobs can be handled best from the seafloor, the Sealab III program was to move deeper into the oceans and develop the tools and technology needed to work there. To meet these needs, the Sealab II habitat was modified extensively for operations to depths of over 600 feet (182.9 m) (Fig. 4-7) and subsequently named Sealab III. Modifications inside were equally extensive. The program plan called for five or six 8-member teams composed of navy and civilian divers to spend 12 days on the seafloor at a depth of 600 feet (182.9 m). Emphasis was on physiological testing, psychological evaluation, military salvage techniques, underwater construction, and evaluation of thermal protection equipment. Civilian programs involved marine biology and geology. Operational require-

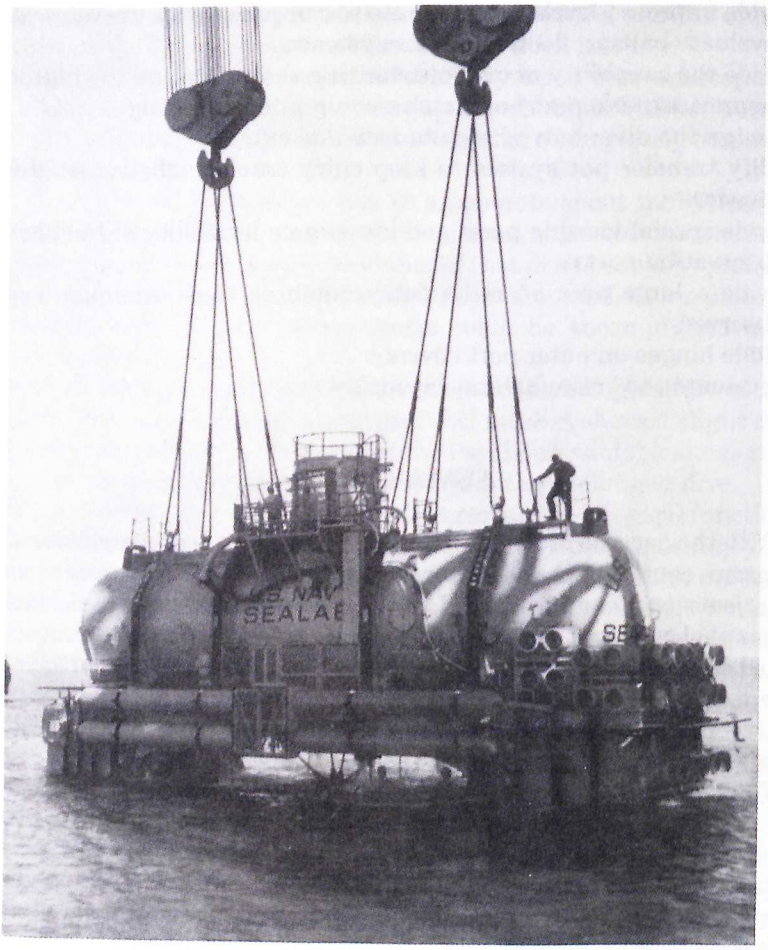

Figure 4-7. Sealab III habitat. (*Official U.S. Navy photograph.*)

ments were to provide a capability for extending diver operations to continental shelf depths.

Sealab III had a succession of equipment problems that caused the postponement of the operation for 18 months. The original planned depth was less than 400 feet (122 m); however, with each delay, the project was moved deeper and deeper until the habitat finally was placed on the seafloor on February 18, 1969, at a depth of 610 feet (186 m).

While still undergoing final checkout of the habitat, the navy's string of successful missions came to a tragic end. A civilian aquanaut, Barry

Cannon, died due to human error. Someone had failed to place the CO_2 scrubbing material in his rebreather. This represented the first known death of a saturation diver participating in an undersea program and caused the navy to abandon not only the Man-in-the-Sea series of programs but to lose all interest in housing humans on the deep seafloor. They scrapped the Sealab III habitat and began to look at other means of accomplishing undersea work.

CONSHELF III, 1965

At 4:15 P.M. on September 21, 1965, aquanauts of the U.S. Navy's Sealab II program were making their afternoon dive in the cold, dark waters of southern California. At this same instant (15 minutes after midnight, September 22, 1965), oceanauts of Conshelf III landed on the floor of the Mediterranean Sea just off the Cap Ferrat lighthouse near Monaco at a depth of 328 feet (100 m). This was to be the beginning of a 22-day seafloor experiment. Six men made up the Conshelf team under the leadership of André Laban, an engineer with fourteen years of experience with Cousteau's undersea group.

A year already had been spent in training, testing and construction of the facilities, and experimental dives, including prolonged exposures of sheep and goats to depths of up to 660 feet (201.2 m) using a helium-oxygen breathing mixture. On the successful completion of these studies, a 3-day experiment was conducted in which Dr. Charles F. Aquadro and Dr. Jacques Chouteau lived in a chamber at a depth equivalent to 400 feet (122 m) of seawater (Cousteau, 1966).

A 4-day trial dive also had been conducted in Monaco Harbor from August 28 to September 2 to a depth of 85 feet (25.9 m) during which the six aquanauts tested the systems and learned to function from an underwater house (Fig. 4-8).

The Conshelf III habitat was a two-story, spherical structure 18 feet (5.5 m) in diameter (Fig. 4-9). The lower floor contained diving, sleeping, and sanitation facilities; the upper floor was for dining, communications, and data gathering. The steel globe rested on a 48 × 28 foot (14.6 × 8.5 m) barge that held 77 tons of ballast, water ballast tanks, and reservoirs of helium, oxygen, and compressed air. Two small decompression chambers also were located on the barge. Each held three men and could be released from the barge in the event of an emergency and carry the aquanauts to the surface, thus serving in effect as underwater lifeboats. The total habitat system, including the barge, weighed 140 tons.

September 17, 1965, had been fixed as the date for launching Conshelf III, and festivities with a bit of fanfare had been arranged to celebrate the

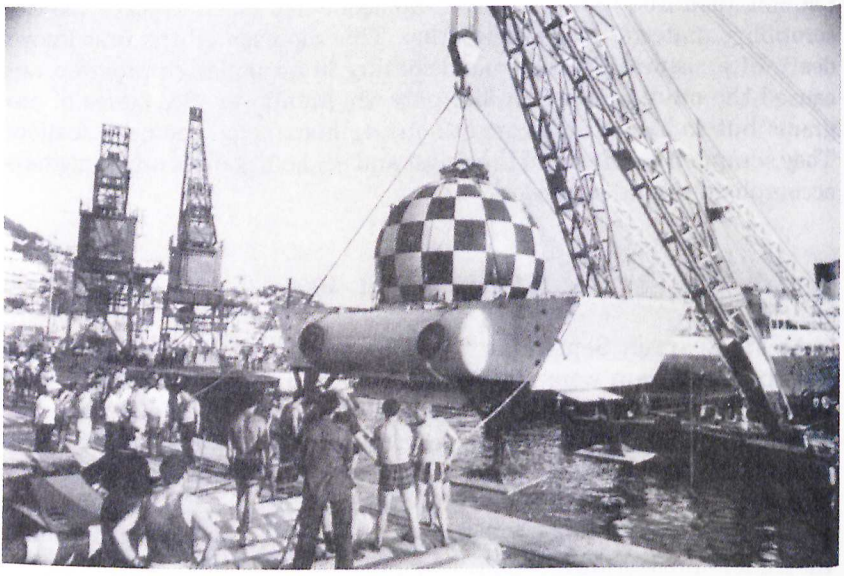

Figure 4-8. External view of Conshelf III habitat. (*From J. Cousteau, 1966, Working for Weeks on the Seafloor, Natl. Geogr.* ***129****(4):502–503; © 1966 National Geographic Society.*)

occasion. Although the weather began to worsen, ceremonies were concluded and the aquanauts sealed into the habitat and pressurized to a depth of 328 feet (100 m).

The habitat was towed to the dive site, and preparations began for submerging. Now the threatening weather broke and damaged power and communications cables from shore, resulting in the habitat's being towed back to Monaco harbor where the aquanauts remained inside under pressure for 4 days while repairs were made. When repairs were completed, Conshelf III again was towed to the site with the assistance of five vessels, the diving saucer, and a half-dozen launches and rubber boats. Following many hours of surface preparations, the habitat was lowered to the seafloor at midnight on September 21. Figure 4-10 illustrates the operational configuration of the Conshelf III program. Once on the seafloor at the planned depth of 328 feet (100 m), the aquanauts checked out all systems and began preparations for conducting the experimental program.

Water temperature outside the habitat was a cool 50° to 55°F (10° to 12.8°C). Inside, because of the high thermal conductivity of helium, the

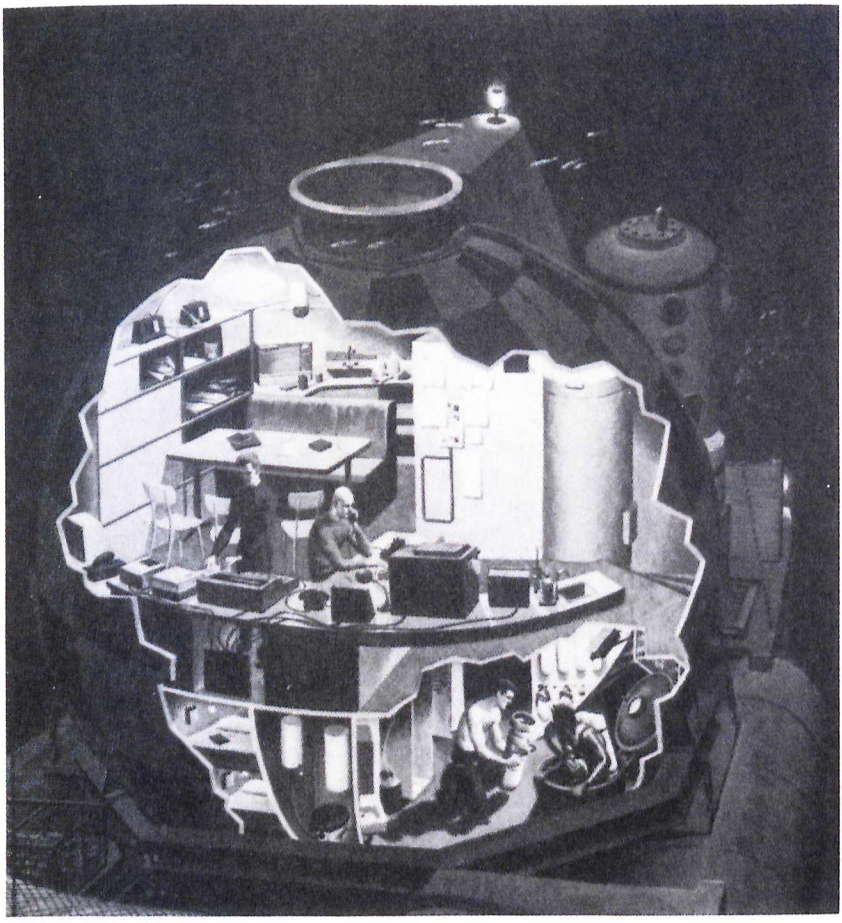

Figure 4-9. Internal view of Conshelf III habitat. (*From J. Cousteau, 1966, Working for Weeks on the Seafloor, Natl. Geogr.* ***129****(4):518-519; © 1966 National Geographic Society.*)

temperature was maintained at 90°F (32.2°C), about 4° warmer than that selected by aquanauts in Sealab II.

The breathing mixture used both in the habitat and on diving excursions was 2.5% oxygen and 97.5% helium. Most dives were made with hookah (air) hoses with backup scuba cylinders available for use in emergencies or for short dives. Vertical excursions were limited to 33 feet (10 m) above and 82 feet (25 m) below the 328-foot (100 m) saturation depth. These limits were not exceeded because the aquanauts could

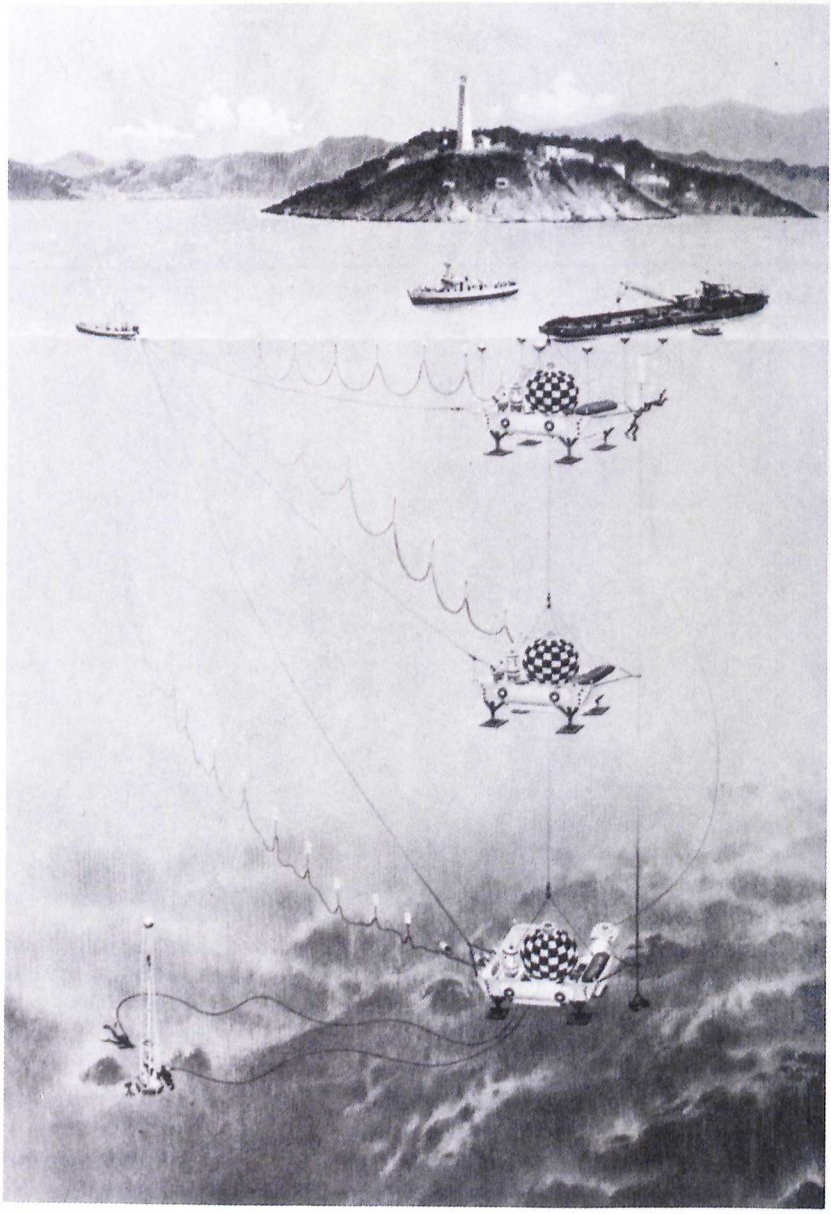

Figure 4-10. Artist's conception of Conshelf III operation. (*From J. Cousteau, 1966, Working for Weeks on the Seafloor, Natl. Geogr.* ***129****(4):510;* © *1966 National Geographic Society.*)

service the uppermost portion of the habitat without going above these limits, and it was impossible to descend to a depth of more than 410 feet (125 m) because of the length of the hookah hoses (Laban, 1965). The ascending and descending excursions produced no detectable problems for the aquanauts.

The hookah hose actually was two hoses. One carried breathing gas from the habitat to the aquanauts, and the other carried exhaled gas back to the habitat, where CO_2 was removed and oxygen added. As described by Cousteau, "The oceanaut at the end of this giant respiratory system wore two heavy foam-rubber wet suits; on his chest was our new, two-way regulator for high-pressure heliox; and on his back, he carried a conventional Aqua-Lung filled with heliox" (Cousteau, 1966, p. 511).

To aid in protecting aquanauts from the cold, each was furnished with a specially designed rubber vest containing tiny ebonite spheres. Even with this special vest, time spent in the water was limited by cold, not fatigue. The use of small spheres for diving suit insulation since has been found to be quite effective.

The life-support system for Conshelf III represented a significant advance. A cryogenerator circulated breathing gases, froze out carbon dioxide and other noxious gases, and served as the dehumidifier and deep freezer. The life-support system also included gas analyzers, which could be monitored both inside the habitat and at the control station in the lighthouse on shore. This system was backed up by a miniaturized mass spectrometer that monitored all the gases in the habitat.

A chronic problem experienced during Sealab II also encountered by Cousteau in Conshelf III was the constant leaking of helium into electronic equipment. Not only did this cause great consternation with regard to the cryogenerator, but it played havoc with the closed-circuit TV system. In Sealab II, the TV problem was solved by placing the cameras outside the habitat in the water, aimed through the ports. In Conshelf III, the problem was solved by replacing television tubes every few days at an average cost of $250 per day.

The now-routine problem of communication in a helium atmosphere again was experienced. The most reliable means of communication was found to be written messages sent to the surface either by displaying them before the TV monitor or by using the electrowriter, a device whereby the aquanaut writes in longhand in the habitat and a pen on the surface simultaneously writes a duplicate at the other end of a connecting cable.

On the fourth day, a severe storm struck the dive site with swells the heaviest in that area since 1947. The storm halted some seafloor projects and damaged the A frame supporting the power and communication cables that linked the habitat to shore. The damage was repaired during

the height of the storm, preventing the necessity of reverting to emergency power and bringing the aquanauts to the surface prematurely.

The aquanauts were impervious to the direct effects of the storm, though the swells were so large they caused the water in the habitat entrance to rise and fall 2 inches (5.1 cm). We experienced a similar situation in Puerto Rico while residing in the La Chalupa habitat at a depth of 100 feet (30.5 m). One chronic annoying effect of a change of water level in the entrance is the constant need to clear the ears due to the resulting change of pressure inside the habitat.

One of the primary work tasks carried out during Conshelf III was assembling components of a production-type oil well head, a vertical stack of pipes and valves referred to as a Christmas tree. On the fifth day, this 5-ton monster was lowered to the seafloor about 150 feet (45.7 m) downslope from the habitat, where it was placed at a depth of 370 feet (112.8 m) (Fig. 4-10). Because of heavy swells from the storm, lowering the Christmas tree was a difficult task, and it was an hour before it rested on the seafloor and was detached from the lowering hook.

To make the work project more realistic, the Christmas tree had been fitted with a compressed air tank to create internal pressure, thus simulating a working wellhead. The aquanauts were required to perform a number of complicated and tedious tasks, including threading a stiff wire through a thick pack of pressure-proof seals and replacing a 400-pound (181.4 kg) valve while it was under pressure of 2500 psi (176 kg/cm^2). This latter job was accomplished in 45 minutes, faster than it ever had been performed on shore by experienced oil well hands. During this work, the divers were supported periodically by the diving saucer, also depicted in Figure 4-10, near the habitat.

In general, the aquanauts performed well and demonstrated that divers could perform hard work in the open sea at depths as great as 370 feet (112.8 m). Average daily time spent in the water was 2½ hours, with a maximum time for one diver in one day of 7 hours.

Although Conshelf III had been scheduled to last for 2 weeks, with about 8 days lost because of the storm, the seafloor program was extended to 22 days. Throughout the period, the program was plagued with equipment failures and engineering problems. As in the previous seafloor programs of Link, the U.S. Navy, and Cousteau, the aquanauts were able to fix, improvise, and solve the succession of difficulties.

On the evening of day 22 (October 13, 1965), ballast was released and compressed air forced into water ballast tanks. The habitat began to rise to the surface, controlled completely by the aquanauts inside, with the diving saucer used as an observation platform during the 3-minute rise. Total bottom time for Conshelf III was 21 days, 17 hours, and 16 minutes. The aquanauts began their 84-hour decompression while the support

ship *Calypso* was towing the habitat to Monaco harbor. Including decompression time and the 4 days waiting out the storm, they had spent 30 days, 10 hours, and 52 minutes under pressure. Other than fatigue, the long stay on the seafloor and lengthy decompression had no adverse medical effects. Cousteau stated it well: "Conshelf III was an epic of triumphant men and failing machines" (Cousteau, 1966, p. 537). He continued:

> I think Conshelf III contributed significant gains to the art of occupying the deep sea bottom: We proved our high-pressure breathing system on its first application. By using incompressible vests, we showed that full suits of microbead material will lessen hardship for future oceanauts. By reducing the ties to the world above, we enabled the station to survive weather that would have forced earlier undersea installations to close down. (Cousteau, 1966, p. 537).

COMMERCIAL INTEREST IN SATURATION DIVING, 1965-1966

While the experiments of the U.S. Navy and Cousteau were being planned and executed, interest in saturation diving was developing in the commercial diving field. In August 1965, at the same time that the open-sea programs of Sealab II and Conshelf III were underway, two men lived in a small chamber for two days at a depth of 650 feet (198.2 m) at the Ocean Systems' Diving Research Facility at the Tonawanda Research Laboratory of Union Carbide Corporation, Tonawanda, New York. This deep dive really was a continuation of Link's Man-in-the-Sea program. Prior to, during, and following this exposure, extensive medical studies were carried out (Hamilton, et al., 1966). The postdive examination of the data revealed that all findings were normal except for an average weight loss of 5 to 6 pounds. During the compression, both divers, Arthur D. Noble and Robert W. Christensen, reported slight dizziness, as well as a fine hand tremor and discomfort during articulation of the large joints. In this dive the compression rate was 10 feet per minute (3.0 m per minute). Similar reports had been received about a deep dive conducted by the Royal Navy. These symptoms later were to be known as the high-pressure nervous syndrome and have been a chronic problem in many subsequent deep dives. An interesting feature of this experimental dive was that the two divers breathed a 90% neon-10% oxygen mixture for 30 minutes at the 650-foot (198.2 m) depth with no deleterious effects.

The investigators concluded that "detailed medical, physiological and psychological measurements taken in the course of this dive show beyond a reasonable doubt that man can reside for prolonged periods of time

anywhere on the continental shelf without acute or latent detriment to his health and without a significant impairment of his functionality" (Hamilton et al., 1966, p. *i*).

The first commercial open-sea application of saturation diving was conducted by Marine Contracting of Southport, Connecticut, in the fall of 1965 about the same time that Conshelf III was completed. The location was in Smith Mountain Dam, Virginia, on the Roanoke River about 35 miles (56 km) southeast of the city of Roanoke. The dam, which rises 227 feet (69.2 m) above the stream bed, created a 40-mile-long (64.4 km) lake covering some 20,000 acres (8094 hectares). Approximately two and a half years had been spent filling the lake behind the dam, and construction costs approached $100 million. During the testing procedure, the turbines operated as planned during the generation phase. During the pumpback phase, however, harmonic resonance was encountered in the upstream trashrack, and, as a result, trashracks were destroyed on two units located at a depth of 135 feet (41.1 m) and 205 feet (62.5 m), respectively, with the lake at normal pool elevation.

This problem coincided with the developing interest in saturation diving by some commercial diving firms. As a result, it was decided to develop a saturation diving system to tackle the Smith Mountain Dam project under a contract to Marine Contracting Inc. Simultaneously a chamber was fabricated, breathing hardware built, a hot water diver heating system devised, and a team of divers selected. Two four-man teams were to operate on the basis of 1 week saturation and 1 week out. The work schedule called for a 12-hour day with two 2-man dives per day operating from the submersible decompression chamber (Wiswell, pers. commun.).

It was determined that four saturated divers living at a depth equivalent to 190 feet (57.9 m) of seawater working two 2-hour shifts per day could accomplish the same amount of work as 32 divers operating from the surface. The alternative to using divers was to drain the lake, which would have resulted in decommissioning the dam for at least two years (Marine Contracting Inc., 1965).

A diving system was developed for this job by the Underseas Division of Westinghouse Electric Corporation under the direction of W. J. O'Neill and Alan Krasberg. Named Cachalot, it was the first commercial saturation diving system ever used. There were several differences between this system, which could operate to depths of 450 feet (137.2 m), and the habitats already described. The commercial divers lived on the surface in a DDC and commuted to the bottom in a 5 × 8 foot (1.5 × 2.4 m) submersible decompression chamber (Fig. 4-11). Divers remained saturated for five days at a time (Wiswell, 1965).

The deck chamber contained an entry lock and two compartments separated by a hatch. Measuring 7 × 21 feet (2.1 × 6.4 m), it was

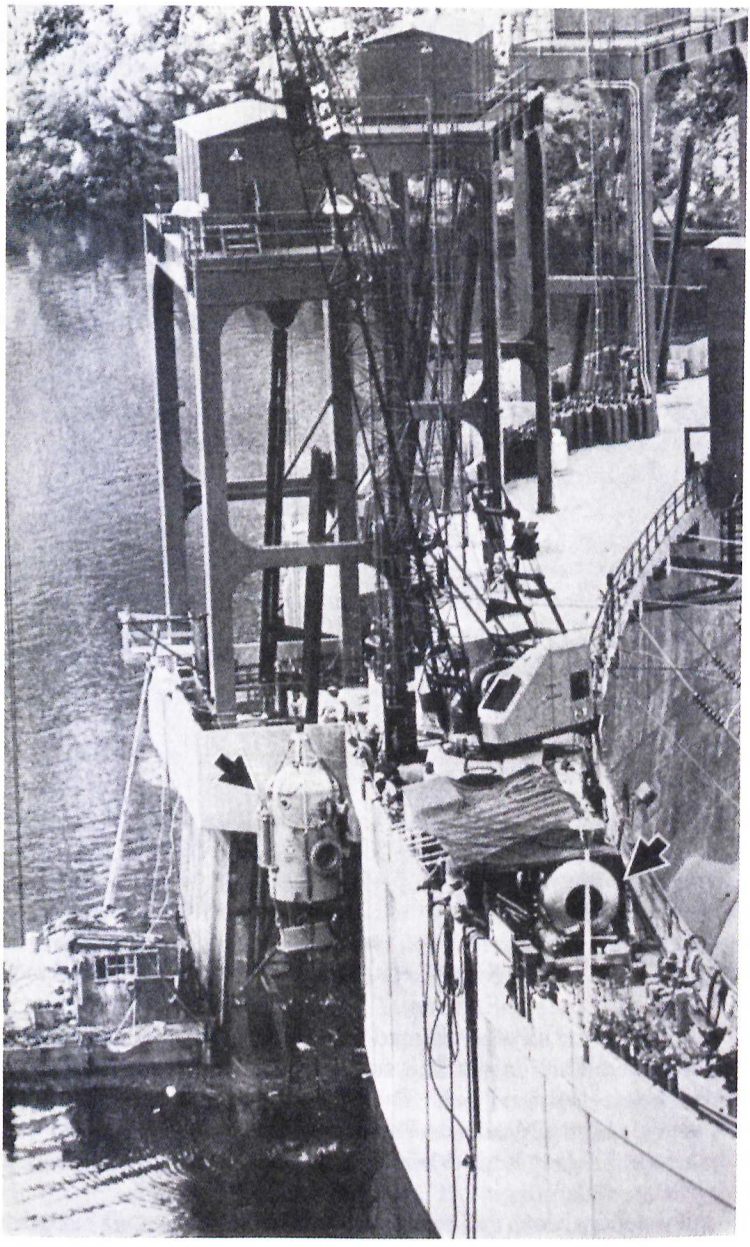

Figure 4-11. Saturation Diving System Used at Smith Mountain Dam. (*From 'Week-Long Dives' Save Millions, Eng. News Rec., Sept. 30, 1965,* © McGraw-Hill, Inc. All rights reserved.)

air-conditioned and equipped with tables, bunks, and a small medical lock used for transfer of food and other supplies. The submersible chamber had a bottom hatch used for entrance and exit in the water and a side hatch used to enter and exit the deck chamber on the surface. The life-support system included electricity, lights, telephone, oxygen sensors, and a CO_2 removal system.

Large cylinders of premixed gases (oxygen, helium, and nitrogen) attached to the outside of the submersible chamber were interconnected through a manifold system. The breathing mixture, which varied according to the depth of the dive, flowed through a pressure-reducing regulator to the diver by the air hose (Wiswell, 1965). Divers wore breathing bags on their chests and CO_2 canisters on their backs.

With water temperature about 40°F (4.4°C), provision was made for pumping hot water from the surface to circulate through tubes in the diving suits, finally exiting at the neck. The water was heated to 115°F (46.1°C) on the surface, which reduced to about 105°F (40.6°C) by the time it entered the diver's suit at the bottom.

Work was performed out of the submersible chamber using 50-foot (15.2 m) semiclosed, mixed gas hookah units. In addition to the breathing gas supplied from the surface, the submersible chamber had emergency tanks that could support the divers for two days. It also had a padded interior and seat belts for protection in the event of an emergency ascent.

The Smith Mountain Dam operation entailed 800 man-hours under pressure over a period of 16 weeks at an average depth of 135 feet (41.2 m). During the course of the job, the divers averaged 3 hours and 45 minutes per dive, for a total of 15 man-hours in the water per day, a schedule maintained throughout the project. Decompression in the deck chamber required 30 hours. The project was successful technically and economically and paved the way for the open-sea commercial saturation diving operations that followed.

Less than a year later, in August 1966, a successful open sea saturation working dive was completed in the Gulf of Mexico about 30 miles (48 km) south of Empire, Louisiana (Anon., 1966). In September 1965, Hurricane Betsy had destroyed an eight-legged oil production platform in 200 feet (61 m) of water. This debris had to be cleared away so that nothing protruded above the mud line. The same Cachalot saturation diving system used at Smith Mountain Dam was transported to Louisiana and mounted on a 300-foot long (91.5 m) barge along with a 250-ton crane (Fig. 4-12).

The job was hazardous and difficult. Divers had to cement closed eight wells, necessitating many underwater connections, attach explosive charges around steel parts of the sunken platform, attach hooks, use cutting torches, all in water of about 55°F (12.8°C) in an average depth of 159 feet

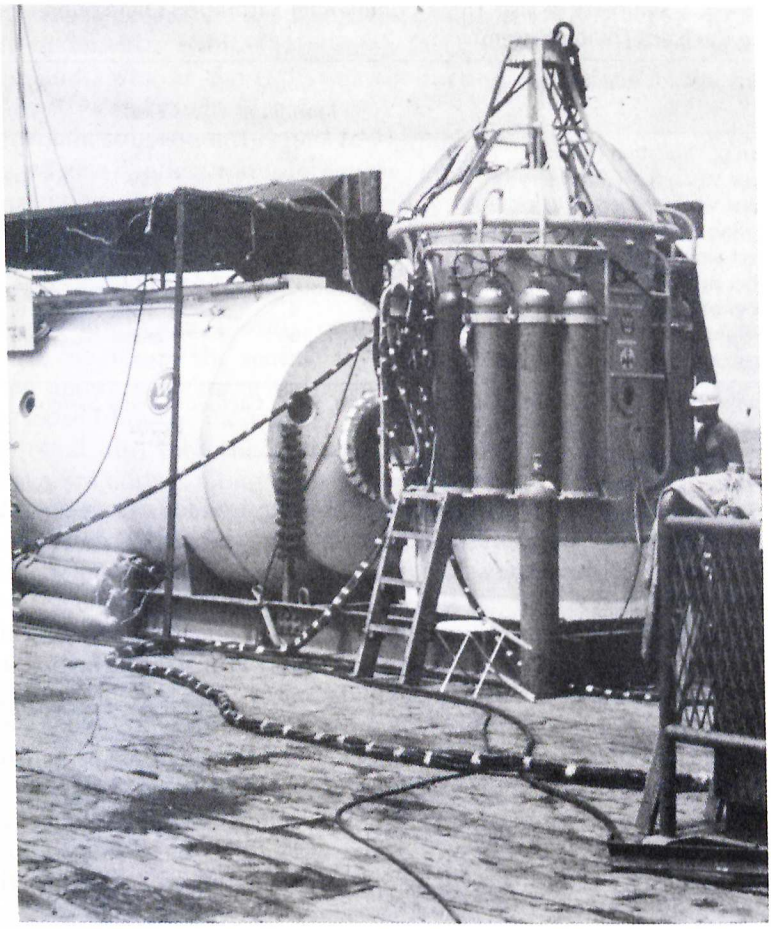

Figure 4-12. Cachalot D commercial diving system at Gulf of Mexico Site. (*Photo by James W. Miller.*)

(48.5 m), with the deepest dive being to 240 feet (73.2 m). Six divers were saturated at one time for a 6-day period. They worked in the water for 5 to 6 hours at a stretch, with the average dive time being slightly over 5 hours per man (Wiswell, pers. commun.). Approximately one day was spent in decompression, followed by a crew rotation. During the four-month operation, divers spent 3600 man-hours in the water.

Successful completion of this first open-sea working saturation dive demonstrated the advantages of using the technique for long-term diving at depths in excess of about 150 feet (45.7 m). A great amount of work

Table 4-1. Summary of First Three Commercial Saturation Diving Operations Using Cachalot Diving System

	Smith Mountain	*Gulf*	*Rhode Island*
Length of Operation (weeks)	16	15	4
Average Working Depth (feet)	135	159	142
Deepest Working Depth (feet)	200	240	170
Total Man Hours Worked (Bell Time × 2)	800	3600	270
Longest Single Working Dive (hours)	5.20	6.00	6.35
Number of Decompressions	12	18	2
Number of Divers in DDC	4	6	6
Total Number of SDC Dives	160	289	32
Average Water Temperature (°F)	40°	55°	45°

Source: From Westinghouse Underseas Division, 1967, *Cachalot Diving Systems*, Annapolis, Md.

was accomplished in a fraction of the time required for divers operating from the surface. Decompression hazards were reduced because of the small number of decompressions necessary compared to conventional diving procedures.

The success of these two commercial diving operations in saving time and money and reducing danger to divers put saturation diving solidly among the techniques of commercial underwater operators. Immediately following the completion of the Gulf of Mexico job, the Cachalot system was used to prepare underwater pilings for the Jamestown-to-Newport bridge across Narragansett Bay in Rhode Island. Table 4-1 summarizes these first three commercial saturation working dives. It had become clear to commercial diving interests that working dives could be accomplished efficiently with divers living on the surface under pressure rather than having them in a habitat on the seafloor.

While it is of considerable importance to the scientist to stay on the seafloor to make long-term observations and frequent visits to check equipment and obtain samples of sea life, commercial operations could work more effectively using the PTC as a pressurized elevator. Both concepts were to be used in the future.

HYDROLAB, 1966

The successes of Link, Cousteau, and the U.S. Navy stimulated interest in undersea exploration within the academic community. In the spring and summer of 1966, less than a year following the completion of Conshelf III, Perry Submarine Builders, Inc., working with engineers of

Florida Atlantic University, designed and fabricated an 8 × 16 foot (2.4 × 4.9 m) underwater habitat (Hydrolab I). Consultation was provided by Edwin Link, who at the time was conducting operations at the Perry plant in Riviera Beach, Florida.

Hydrolab, subsequently given to Florida Atlantic University by Perry, was used as a shallow water laboratory and classroom in nearby Florida waters and was to serve as an engineering tool, as well as an observation platform and operations base for marine scientists (Florida Council of 100, 1966). The new habitat was dedicated at Florida Atlantic in June 1966 (Fig. 4-13) and was placed at a depth of 40 to 50 feet (12.2 to 15.2 m) off West Palm Beach, Florida, on July 14, 1966. The habitat had no legs and was moored to the seafloor by chains, a semifloating arrangement that produced seasickness in some aquanauts. On one occasion, Hydrolab broke loose from the mooring chains, rose to the surface, and floated 25 miles (40.2 km) into the gulfstream. After that experience, legs and ballast were added, along with a 4-foot (1.2 m) window. A submersible transfer lock also was introduced to permit divers to enter the habitat directly from a dry submersible (Fig. 4-14).

The main structure now was supported on four short legs 3 feet (0.9 m) above the concrete base. The habitat was submerged by venting ballast



Figure 4-13. Hydrolab I habitat during its dedication at Florida Atlantic University in June 1966. (*Courtesy of Robert C. Stevens, Jr., Continental Shelf Associates, Inc., Tequesta, Florida.*)

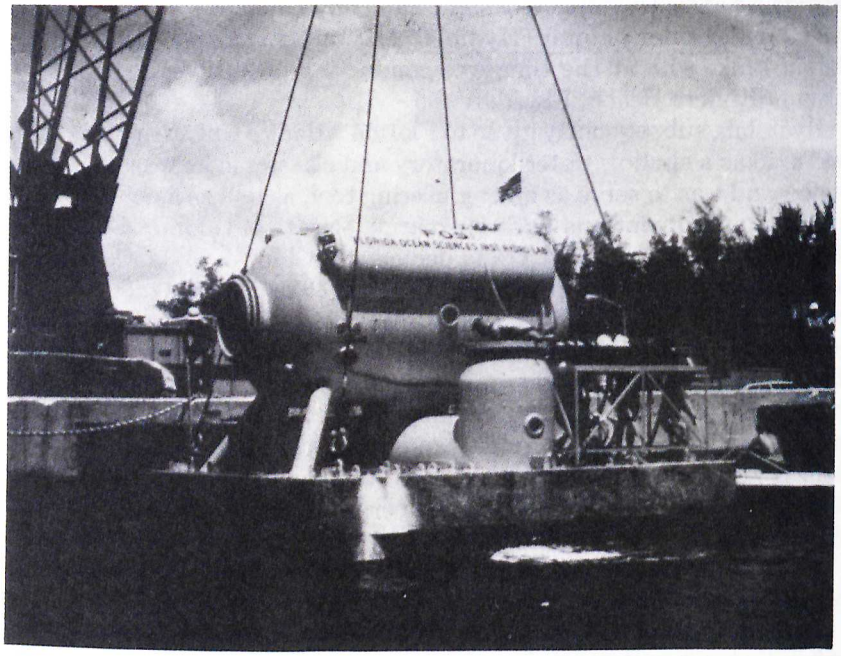

Figure 4-14. Hydrolab habitat following modification in 1967. (*Courtesy of Perry Submarine Builders, Riviera Beach, Florida.*)

tanks in the concrete base and buoyancy tanks located along the habitat cylinder. Pipe fittings projecting from the base permitted the ballast tanks to be filled with air when the habitat was to be raised. Entry into the habitat was through a well at one end, which also functioned as a lock when the chamber pressure was less than ambient. Returning divers entered the trunk one at a time, removed wet suits and accessories, which were stored in the trunk or in mesh bags hung outside in the water (Fig. 5-18), and then showered while crouched within the trunk. Hydrolab aquanauts either stood waist deep in water or straddled the lower opening, standing on the hatch rim. Neither choice was comfortable (High et al., 1973).

During the summer of 1968, Perry Submarine Builders performed a dry transfer of three persons between an oceanographic vessel and an underwater laboratory. The transfer, which took place in a 1-knot current at a depth of 50 feet (15.2 m) off Palm Beach, Florida, occurred during hookup of Perry's four-man lockout submarine, Shelf Diver, and Hydrolab. Mating between the two occurred while the submarine was positioned

over the transfer tunnel that surrounded one arm of the U-shaped entranceway leading to the underside of Hydrolab (Fig. 4-14). After the submarine was fastened to the tunnel, the tunnel was blown dry and the hatch opened, allowing passengers to enter without getting wet.

Also in 1968, a saturation dive took place in which three aquanauts—Dr. Joseph MacInnis, Robert Wicklund, and a student from Florida Atlantic University—spent 50 hours at a depth of 50 feet (15.2 m). The decompression following this saturation was incredibly short, requiring only 4 hours, and was carried out in the water.

Hydrolab also was operated at a pressure of 1 atmosphere on the seafloor during 1968, the only habitat to be used in this mode. Under these conditions the aquanauts would swim to the seafloor, seal themselves in the habitat, and stay for a day or so at surface pressure. When finished, they would open up and return to the surface.

From October 15 to 17, 1969, while in 50 feet (15.2 m) of water off the coast of Palm Beach, Florida, a fuel cell was used for the first time to supply all electrical requirements for Hydrolab (Fig. 4-15). The aquanauts were Wallace Jenkins, Richard A. Waller and Dr. David Youngblood.

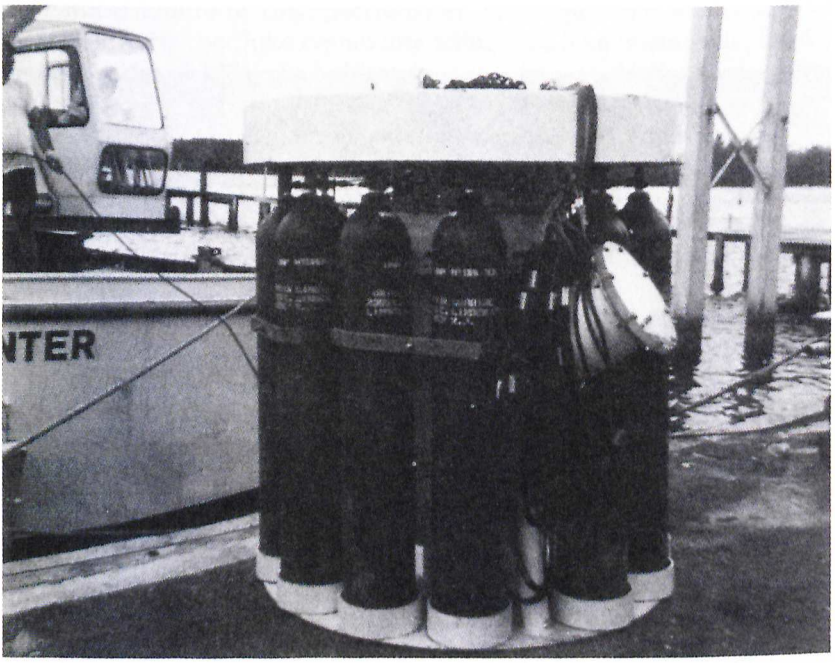

Figure 4-15. Fuel cell used to power Hydrolab during 1969 mission. (*Courtesy of Perry Submarine Builders, Riviera Beach, Florida.*)

The author (Koblick) was a support diver for this project. During testing, they were self-sustained with no topside power umbilicals or seafloor-to-land cables, the first and only totally autonomous seafloor live-in.

Built by Pratt and Whitney Aircraft, the Powercel 8 powered interior and exterior lighting, CO_2 scrubbers, instruments, data-recording and communication equipment, a motor generator set, and a small high-pressure compressor. Weighing 118 pounds (53.5 kg) and occupying 3.2 cubic feet (0.1 m^3), the Powercel could produce up to 5 kw, with hydrogen and oxygen supplied from externally mounted standard gas cylinders.

The Powercel, was located approximately 50 feet (15.2 m) from the habitat, and transmitted power to Hydrolab through cables. A small instrument package mounted outside one of the viewing ports enabled the aquanauts to monitor the status of the generator.

In 1970, Hydrolab was taken out of the water and refurbished at Perry Submarine Builders. The major addition was a life-support buoy to float on the surface above the habitat, permitting Hydrolab to operate for extended periods without manned support on the surface (Fig. 4-16). It was not known at the time that the Germans had designed the Helgoland habitat, supported in the same manner. Other changes included replacing

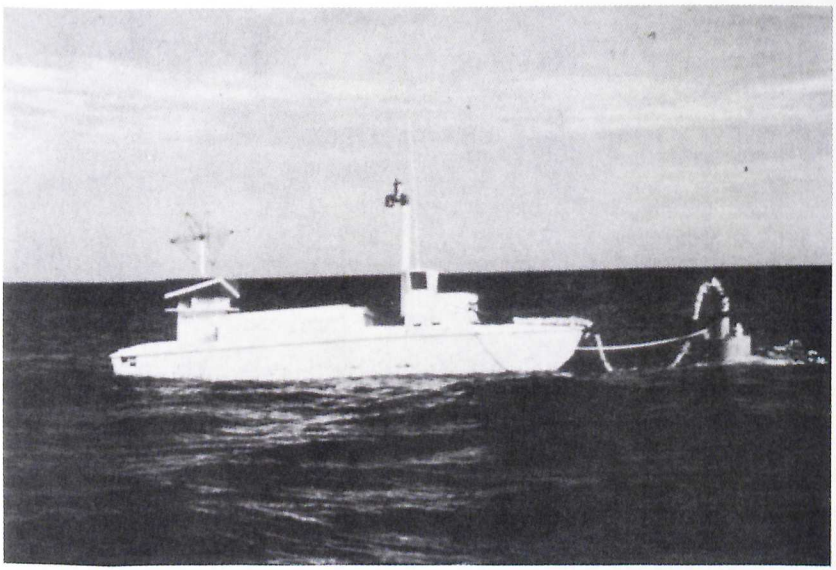

Figure 4-16. Life support buoy for Hydrolab habitat. (*Photo by James W. Miller.*)

the wooden floor in the habitat with steel decking and installing an air-conditioning system. Also added was a portable underwater talking station (PUTS) just outside the habitat. In addition to its use as a talking refuge, it contained several large backup air cylinders and on a few occasions served as a clandestine smoking room.

In March 1971, Hydrolab was moved to a site about 1 mile (1.6 km) off the coast of Freeport, Grand Bahama Island. It was now capable of housing three or four persons for periods of up to 1 week. The life-support buoy contained water, power, and communications, and the habitat was capable of operating at either ambient or surface pressure. The entrance trunk with intermediate hatches allowed aquanauts to lock out should the habitat be pressurized at atmospheric pressure. Interior accessories now included bunks, a shower, a dehumidifier, air conditioning, AC and DC lighting, and the 4-foot viewing port (Fig. 4-17). Decompression following a mission was carried out from inside Hydrolab and was controlled by the aquanauts.

The first saturation dive using this modified facility took place from March 21 to 23, 1971 (Wicklund, 1972). The dive, although scheduled for 5 days at a depth of 50 feet (15.2 m), was terminated after 28 hours due to mechanical failure of the spectrometer. Decompression was completed successfully by the three aquanauts using a 13.5-hour schedule. During the remainder of 1971, the habitat was used for six additional saturation dives and for a variety of filming and educational programs.

Between early 1972 and May 1975, with support from the National Oceanic and Atmospheric Administration (NOAA), Hydrolab was used by 293 different aquanauts saturating in teams of three to four at a depth of 42 feet (12.8 m). An additional 24 aquanauts were saturated at a depth of 60 feet (18.3 m), for a total of 317 aquanauts over the three-year period. As in all previous Hydrolab missions, aquanauts breathed air both in the habitat and while diving. The shortest mission was 24 hours and the longest 13 days, with an average of 6 days for the more than 90 missions completed. With one exception, the missions were devoted to marine science investigations. Project SCORE (Scientific Cooperative Operational Research Expedition), carried out in the spring of 1975, was designed to test descending excursions requiring decompression from the saturation depth of 60 feet (18.3 m). This was the first time decompression excursions had been used from a seafloor habitat. Compressed air again was used as the storage breathing gas and for excursions. During SCORE, four teams of four diver-scientists each spent 5 days at the 60-foot (18.3 m) depth.

In addition to decompression excursions, the aquanauts conducted

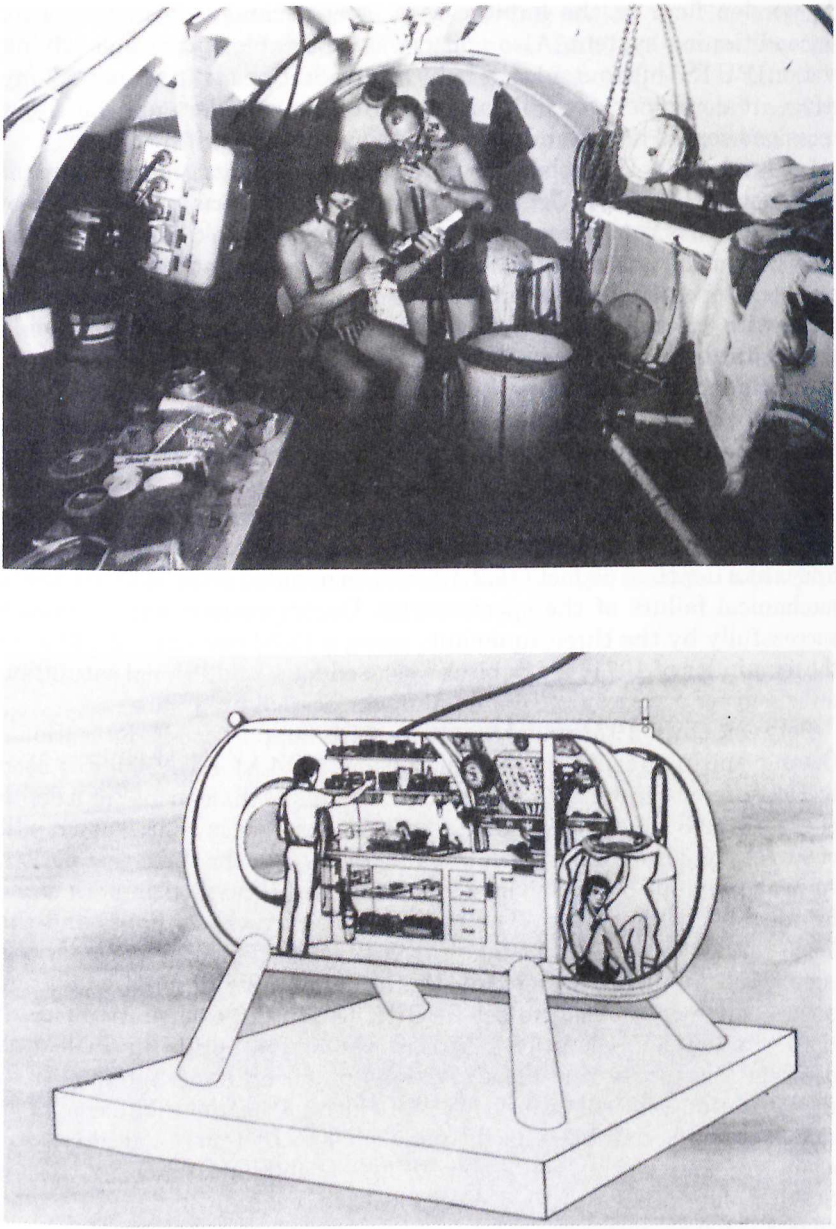

Figure 4-17. Interior view of Hydrolab, 1971. (*Photo courtesy of William High, National Oceanic and Atmospheric Administration, Seattle, Washington; drawing courtesy of National Oceanic and Atmospheric Administration.*)

fish censuses, fish tagging, coral mapping, measurements of the distribution of benthic plants, and geological zonation studies. In each case, data were obtained at depths not readily accessible from the surface because of bottomtime limitations.

Laboratory tests for this mission had been carried out previously at Duke University where eight men were saturated at 60 feet (18.3 m) on air and made excursions (also on air) to depths of 200 feet (61 m), 250 feet (76.2 m), and 300 feet (91.4 m) for a period of 1 hour.

The SCORE open-sea program used the lock-out submersible Johnson Sea-Link for transporting aquanauts from the habitat to the deep dive site (Fig. 4-18). Following the descending excursions, the aquanauts entered the submersible, where they remained for decompression prior to returning to Hydrolab. Decompression time from the 200-foot (61 m) excursions back to the Hydrolab depth of 60 feet (18.3 m) was 19 minutes, with 45 minutes required following the 250-foot (76.2 m) excursions. Final decompression from 60 feet (18.3 m) to the surface was 17 hours and 35 minutes.

An interesting feature of SCORE was the use of the Subigloo habitat as a seafloor safety and communication station (Fig. 4-18). Details of Subigloo are found in Chapter 9. Subigloo was used as a haven during

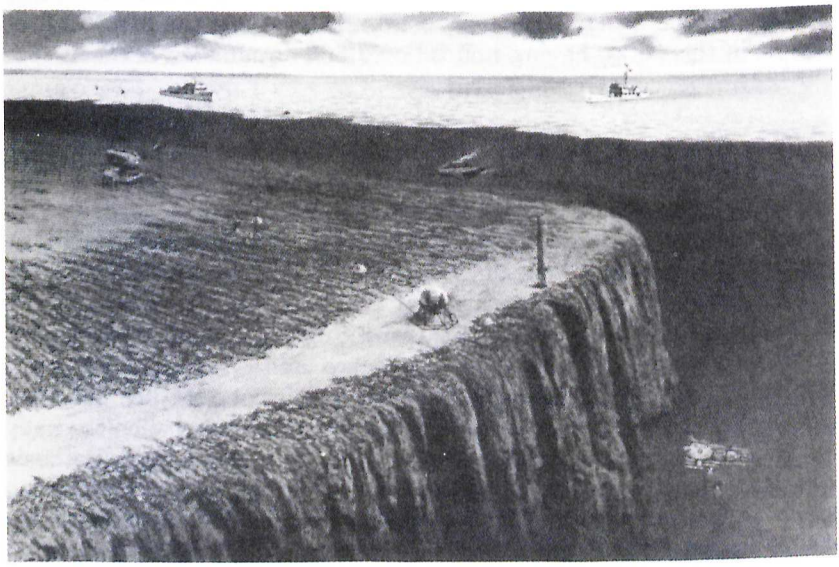

Figure 4-18. Artist's conception of Hydrolab program—project SCORE. (*Courtesy of National Oceanic and Atmospheric Administration.*)

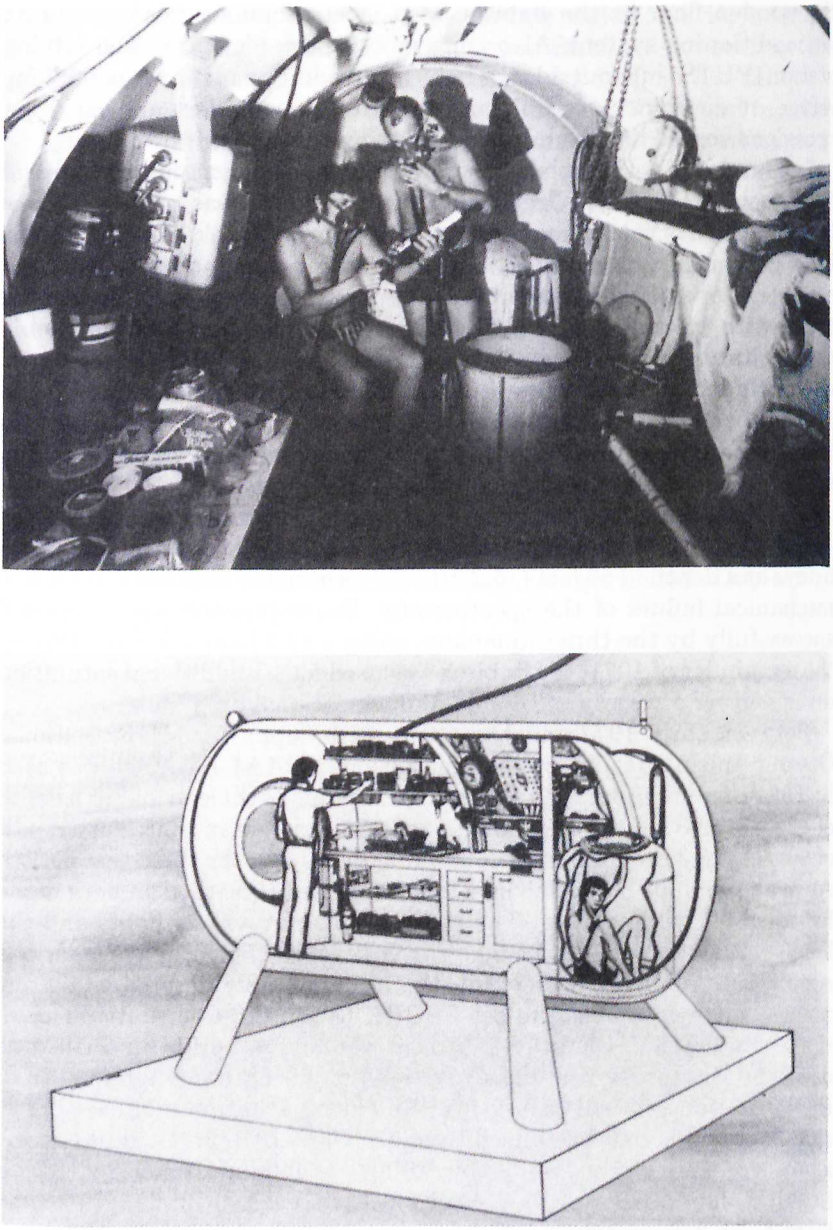

Figure 4-17. Interior view of Hydrolab, 1971. (*Photo courtesy of William High, National Oceanic and Atmospheric Administration, Seattle, Washington; drawing courtesy of National Oceanic and Atmospheric Administration.*)

fish censuses, fish tagging, coral mapping, measurements of the distribution of benthic plants, and geological zonation studies. In each case, data were obtained at depths not readily accessible from the surface because of bottomtime limitations.

Laboratory tests for this mission had been carried out previously at Duke University where eight men were saturated at 60 feet (18.3 m) on air and made excursions (also on air) to depths of 200 feet (61 m), 250 feet (76.2 m), and 300 feet (91.4 m) for a period of 1 hour.

The SCORE open-sea program used the lock-out submersible Johnson Sea-Link for transporting aquanauts from the habitat to the deep dive site (Fig. 4-18). Following the descending excursions, the aquanauts entered the submersible, where they remained for decompression prior to returning to Hydrolab. Decompression time from the 200-foot (61 m) excursions back to the Hydrolab depth of 60 feet (18.3 m) was 19 minutes, with 45 minutes required following the 250-foot (76.2 m) excursions. Final decompression from 60 feet (18.3 m) to the surface was 17 hours and 35 minutes.

An interesting feature of SCORE was the use of the Subigloo habitat as a seafloor safety and communication station (Fig. 4-18). Details of Subigloo are found in Chapter 9. Subigloo was used as a haven during



Figure 4-18. Artist's conception of Hydrolab program—project SCORE. (*Courtesy of National Oceanic and Atmospheric Administration.*)

several excursions and was a critical factor in saving a life during the first SCORE mission.

Following the SCORE project, three or four scientific missions were carried out using Hydrolab before the program terminated and the habitat was transferred from the Bahamas back to Florida in the summer of 1975. During the 90 missions that took place between 1972 and 1975, the program was safely managed, operated, and documented by two operations persons and a part-time administrative assistant. During some missions the surface support was augmented by support divers brought to the site by the aquanauts. This is in sharp contrast to some of the programs to be described in the following pages in which large surface-support teams were required.

In the fall of 1977, Hydrolab was purchased by the NOAA. Following a major refurbishment of both the habitat and the life-support buoy, the system was transported to the U.S. Virgin Islands and emplaced at a depth of 50 feet (15.2 m) off the northeast corner of St. Croix.

Since 1978, over 54 scientific and training missions have been carried out in a continuing program. The missions are devoted primarily to marine science and are selected by a scientific peer review board. Each mission lasts 7 days and is carried out by a team of four aquanauts. The program is operated by the West Indies Laboratory of Fairleigh Dickinson University under a grant from NOAA. Currently Hydrolab is the only habitat still operating. Without question, it has been the most utilized habitat in the world, having housed over 500 aquanauts between 1966 and 1984.

TEKTITE I, 1969

In November 1966, the National Aeronautics and Space Administration (NASA) sponsored a one-day meeting to discuss problems associated with human isolation and confinement in future space missions. One of us (Miller) was asked to speak at this meeting to discuss psychological problems associated with living in the sea and whether these same problems might arise during extended space missions (Miller, 1966*a*).

As a result of this presentation, a series of meetings between the navy and NASA was held to develop a rationale for validating the hypothesis that psychological data obtained in undersea programs could be used to predict and understand problems associated with behavior and effectiveness of space crews. By December 1967, the navy and NASA were considering an undersea space station program, and several proposals subsequently were submitted to the Office of Naval Research. A proposal from the General Electric Company to build an undersea habitat was selected.

Construction funds were to be provided by General Electric in return for government support for the operation of the system once it became seaworthy.

The combined efforts of NASA, the navy, and General Electric formed the nucleus of the Tektite I program. Denzil Pauli and one of us (Miller), then employed by the Office of Naval Research, were named as program director and deputy program director, respectively. It was essential that a meaningful scientific program be conducted on the seafloor to provide NASA with a realistic assessment of crew behavior. In response to this need, the Department of Interior provided the necessary personnel and marine scientific expertise to conduct a seafloor program, which included the other author (Koblick). The project title, Tektite, borrows the name from small meteorites (tektites) that survive the firey plunge through the earth's atmosphere and often come to rest on the ocean floor. The name symbolically linked the program's oceanographic and space scientific interests.

The purpose of Tektite I was threefold: the navy was interested in further studies of diving physiology, the behavior of small crews in isolated conditions, and ocean technology; NASA's interests were centered around small-crew behavior with respect to long-duration space missions; and the Department of Interior was interested in the use of saturation diving to broaden the capability to conduct scientific work on the bottom of the sea. More specifically, the goal of the Interior Department was to extend bottom time and depth in a safe and cost-effective manner, and Tektite I was to be the first long-term use of a nitrogen-oxygen breathing mixture in the open sea.

Tektite I took place from February 15 to April 15, 1969, in Greater Lameshur Bay on the island of St. John in the U.S. Virgin Islands. The duration of the seafloor program was to be 60 days, equivalent to space missions planned for the future and by far the longest saturation dive to date. The aquanauts, all from the Department of Interior, were Richard A. Waller (team leader), John G. Van Derwalker, Conrad V. W. Mahnken, and H. Edward Clifton. Three backup aquanauts also were selected: Ian G. Koblick (author) of the government of the Virgin Islands, Gary E. Davis, and R. Lawrence Phillips, also of the Interior Department.

Program facilities consisted of the habitat, a support barge, a crane barge (with decompression facilities), a causeway pier, and a base camp. The habitat was comprised of two steel cylinders attached to a rectangular steel base and connected by a crossover tunnel (Fig. 4-19). Each cylinder contained a circular upper and lower compartment measuring 12.5 feet (3.8 m) in diameter and 9 feet (2.7 m) high, as well as large hemispherical ports with a cupola located on top of the equipment room for crew observation.

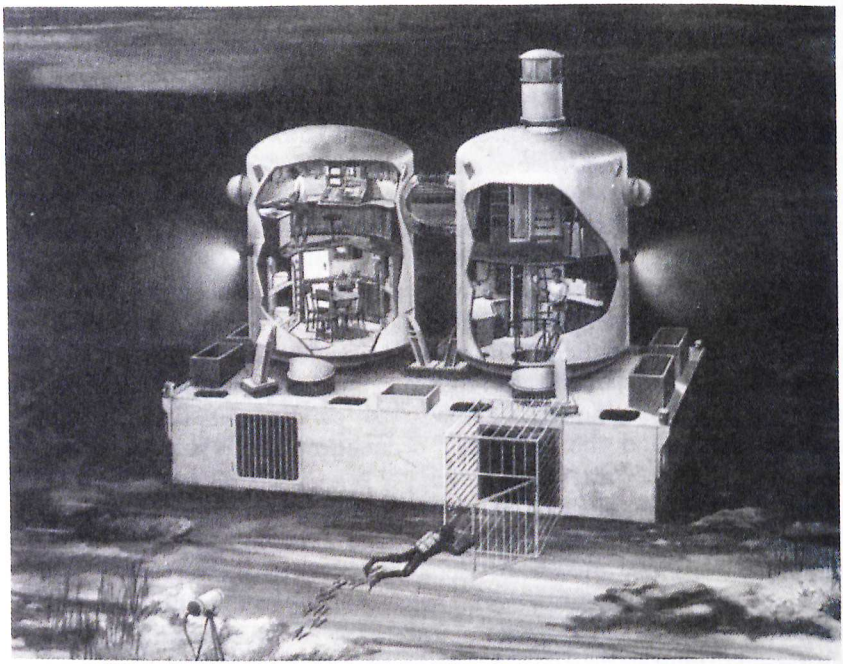

Figure 4-19. Tektite I habitat. (*Courtesy of General Electric Company.*)

The base of the habitat contained two passageways with barred gates at each end. One permitted access to the wet room, and one passed under the normally closed emergency escape hatch beneath the floor in the crew quarters. In addition to providing a rigid attachment for the twin cylinders, the base contained variable seawater ballast tanks and fixed ballast bins to hold the steel punchings and iron pigs necessary for ballast.

Crew quarters included four built-in bunks, drawer space, a sink, a stove, a refrigerator, and a radio and TV set. The bridge contained the environmental control and alarm panels, the communications panel, and other ancillary instrumentation. It served as the habitat control center and as a dry laboratory for the scientists. The equipment room held the electrical system, a large freezer, and a toilet. In the wet room were a freshwater shower, a clothes dryer, storage space for scuba gear, and stainless steel counters for specimen preparation and study.

A surface-support barge provided all utilities and services for the habitat and contained the watch director and psychological monitoring stations. A second barge held the DDC, PTC, and the crane (Fig. 4-20). A

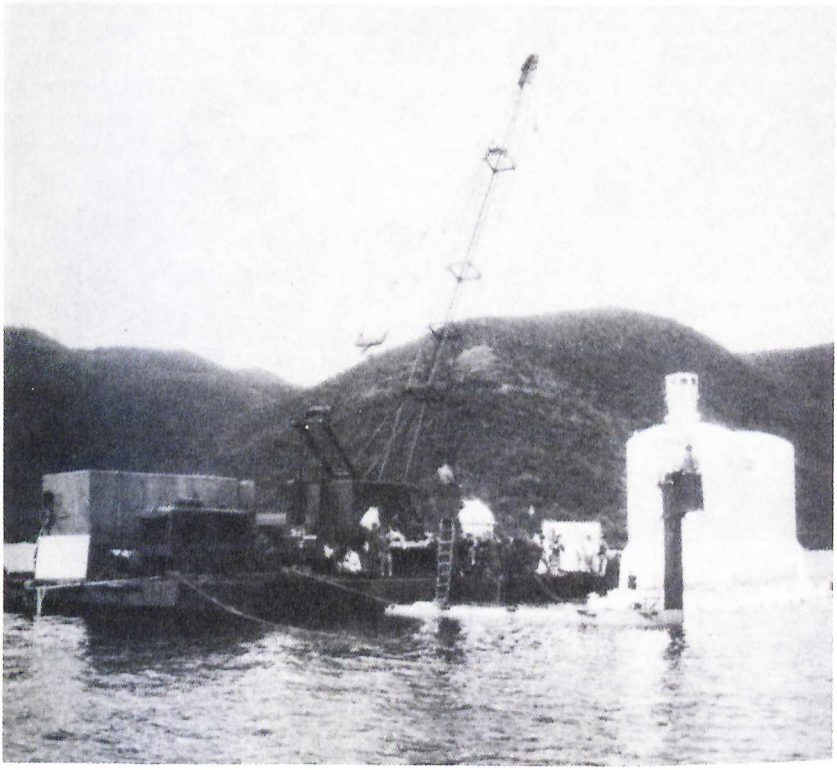

Figure 4-20. Tektite I surface support barge. (*Official U.S. Navy photograph.*)

view of part of the base camp, built by Navy Seabees, is shown in Fig. 4-21. The Tektite base camp in many ways resembled the MASH camp depicted in the long-running television series in terms of both construction and social activity.

The habitat was placed on the seafloor on January 28, 1969, and opened for business on February 14. Pressure inside was equivalent to 43 feet (13.1 m) of seawater. Unlike previous habitat programs in which the habitat descended as a result of negative buoyancy, Tektite was winched down while still 5000 pounds positively buoyant. Once it was on the seafloor, water was admitted to the ballast tanks and pig iron added to achieve the necessary negative buoyancy of 10 tons. The four aquanauts entered the habitat at 10:55 A.M. on February 15. They breathed a mixture of 92% nitrogen and 8% oxygen while in the habitat and air when using scuba for excursions.

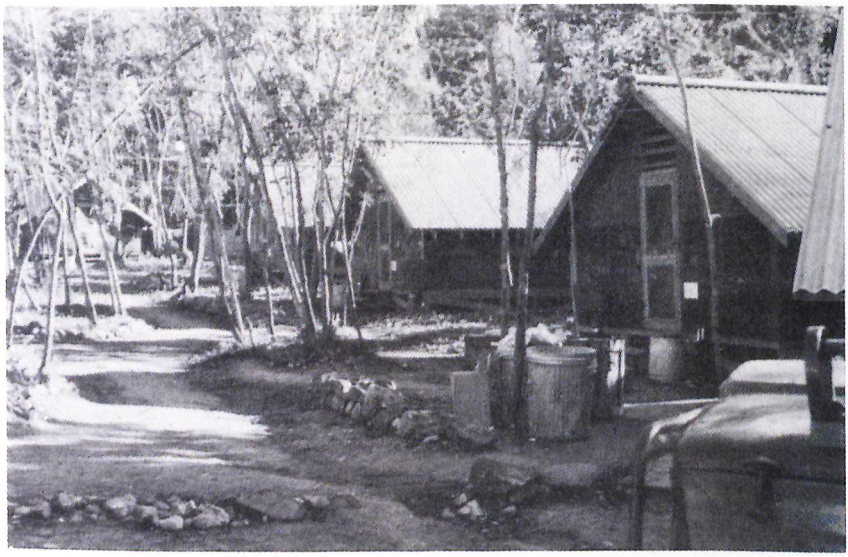

Figure 4-21. Tektite base camp. (*Official U.S. Navy photograph.*)

Table 4-2. Summary of Tektite I Ocean Floor Program

Marine Science	*Psychological*	*Medical*
Environmental factors	Crew behavior measures	General medical examinations
Plankton analysis	Crew selection study	
Spiny lobster behavior	Human performance study	Hematology
Spiny lobster population	Habitability study	Microbiology
Lobstering and fishing	Data collection study	Respiratory/ Pulmonary
Day-night periodicity of fishes		Decompression procedures
Effects of the habitat on marine life		Correlation of medical and psychological data
Effect of light attraction on marine organisms		

Source: After D. Pauli and H. Cole, 1970, *Project Tektite I, A Multiagency 60-Day Saturated Dive Conducted by the U.S. Navy, The National Aeronautics and Space Administration, The Department of The Interior, and the General Electric Co.*, ONR Report DR-153, Office of Naval Research, Washington, D.C.

The seafloor program was divided into three general categories: marine science, psychological, and medical (Miller and Lambertsen, 1970). In the marine science program, more research was planned than could be accomplished during the mission, allowing the aquanauts to select those problems best suited to the situation. A summary of the seafloor program is shown in Table 4-2. The aquanauts in the habitat were assisted in their marine scientific research by the three alternate aquanauts.

The psychological program was designed to obtain data useful for future manned missions in space, as well as undersea research. Areas emphasized were crew size and selection criteria, habitability of the undersea station, and use of time during the mission. To make the data more meaningful for space applications, every effort was made to avoid any contact between the four aquanauts and people on the surface. This isolation, when combined with a meaningful marine science mission, contributed to the significance of the study. Psychological data were collected using 24-hour visual and auditory monitoring of the crew, which resulted in over 400,000 individual observations.

The biomedical part of the program had two purposes: the aquanauts' medical safety and evaluation of possible psychological effects of long-term saturation exposure using a nitrogen-oxygen breathing mixture. Particular attention was given to the functioning of the pulmonary, circulatory, and nervous systems (Pauli and Cole, 1970). The aquanauts

Marine Science	*Psychological*	*Medical*
Use of Artificial reefs		
Geological bottom mapping		
Biogenous sand		
Reef diagenesis and lithification		
Effects of organisms on sedimentation		
Storm modifications		
Carbonate mud		
Bottom rock weathering		
Sedimentology techniques		

underwent a week of extensive medical examinations at the University of Pennsylvania Hospital Research Center prior to the mission. Many of these studies were continued during the 60-day saturation and for 1 week following the mission (Miller and Lambertsen, 1971). Additional laboratory studies were conducted to determine the surface interval prior to the onset of bends in the event an aquanaut surfaced accidentally after becoming saturated at a depth of 50 feet (15.2 m). Experiments by Edel (1970) showed that the aquanaut probably would not be in danger if the surface interval was less than 15 minutes (Beckman and Smith, 1972).

Tektite I aquanauts spent 432 man-hours in the water during the 60-day mission. Toward the end, they were spending as many as 5 hours per day in the water. The overall daily average was about 2 hours per man, approximately the same as that of Conshelf III but far less than the 5 to 6 hours spent in the water each day by the divers using the Cachalot system in the Gulf of Mexico in 1966. Generally the marine science missions were completed, although alternate programs were inserted due to various equipment difficulties. The only biomedical problems of significance were ear infections, which caused the loss of many days in the water by each aquanaut.

As was the case in previous seafloor programs, the major problems centered around equipment failures. Tektite I encountered continual difficulties with the CO_2 removal system, the TV cameras, the surface resupply system, gas monitoring equipment, and myriad of other problems. Consequently aquanauts spent significant amounts of their time repairing equipment, activities that interfered with in-water marine science programs.

On excursions the aquanauts used either 200-foot (61 m) air (hookah) hoses or scuba. Because of the local topography, vertical excursions were limited to an upward depth of 22 feet (6.7 m) and a downward depth of 85 feet (25.9 m). Lateral excursions extended to distances of 1800 feet (549 m) from the habitat. Water temperature near the bottom was about 70° to 75°F (21° to 24°C). Inside the habitat, temperature could be controlled over a range of 75° to 90°F (24° to 32°C). The aquanauts preferred between 80° and 85°F (26.7° to 29.4°C). Humidity was controllable between 42% and 60%, with a preferred setting of about 50%.

On April 15, 1969, the four aquanauts left the habitat and swam the 400 feet (122 m) to the pressurized PTC located directly beneath the crane barge. The capsule was lifted to the deck and mated to the decompression chamber, where the aquanauts underwent a decompression of 19 hours and 22 minutes. Stage decompression was used with depth changes of 1 foot per minute. The aquanauts left the chamber at 8:08 P.M. on April 15, 1969, having encountered no difficulties in decompression (Fig. 4-22).

General conclusions and recommendations of Tektite I are summarized in Table 4-3.



Figure 4-22. Tektite I aquanauts being greeted following 60-Day seafloor mission. (*Official U.S. Navy photograph.*)

Table 4-3. Summary of Conclusions and Recommendations from Tektite I

Conclusions	*Recommendations*
Aquanauts can live safely and work in a hyperbaric nitrogen/oxygen atmosphere saturated at 43 feet (13.1 m) with ascending and descending vertical excursions to 22 feet (6.7 m) and 85 feet (25.9 m) respectively.	Preventive measures to curb aquanaut ear infections should be developed.
Aquanauts surfacing accidentally from a depth of 43 feet (13.1 m) do not require recompression treatment prior to a surface interval of about 15 minutes.	Future habitat crews should include a diver-engineer responsible for equipment maintenance and housekeeping.
Prolonged exposure in the environmental conditions of Tektite I did not result in any unusual microbiological hazard other than ear infections.	Designs of habitats for future missions should reflect the need for work areas compatible with the needs of the aquanaut users.
Saturation diving offers great advantages to marine scientific investigations.	Future habitats should be designed to allow leveling after the habitat has been placed on the ocean floor.
Long excursions appear feasible and would be applicable to civilian and military needs.	Habitats should be designed for transportation and launch in less-than-favorable seas.
Aquanauts swimming in warm tropical water were physiologically bound only by vertical limits imposed by decompression.	Special emphasis in future missions should be placed on establishing fully adequate surface and free-swimmer communication systems.
	Hookah masks, with communication capability between divers and the habitat, should be provided in subsequent programs and adequate, convenient space should be provided outside the habitat for stowage of hookah hoses not in use.

Source: Based on information in D. Pauli and H. Cole, 1970, *Project Tektite I, A Multiagency 60-day Saturated Dive Conducted by the U. S. Navy, the National Aeronautics and Space Administration, the Department of the Interior, and the General Electric Co.*, ONR Report DR-153, Office of Naval Research, Washington, D.C.

TEKTITE II, 1970

Tektite I was another in a series of seafloor habitat successes that continued to attract both national and international attention. Other government agencies, as well as members of the academic and industrial community, supported a continuation of such programs.

The U.S. Navy had abandoned its own man-in-sea experiments and no

longer had an operational interest in seafloor habitat projects (especially in shallow water). Consequently when Tektite I was completed, the navy terminated the project and moved the habitat back to Philadelphia. Hopes for a follow-on project looked dim. The authors and Richard A. Waller (team leader for Tektite I) were convinced that a Tektite II program would be beneficial for both the scientific and technological communities. They were able to convince the Department of Interior's under secretary, Russell Train, who in turn convinced Walter Hickel, secretary of the interior, that a continuing program was desirable under the direction of the Department of Interior. The Tektite habitat refurbished by the General Electric Company once again was transported to the Virgin Islands by the navy, and Tektite II got underway.

The program was managed by the author (Miller) and deputy program manager Richard A. Waller. They eliminated the navy crane barge and other barge and shipboard support facilities as being too costly to operate and requiring too much manpower. Under the direction of the author (Koblick), shore-based support facilities were established for habitat life support, a command and control center, and diving support. A decompression system was placed on a barge and positioned next to the diving support facility (Fig. 4-23).

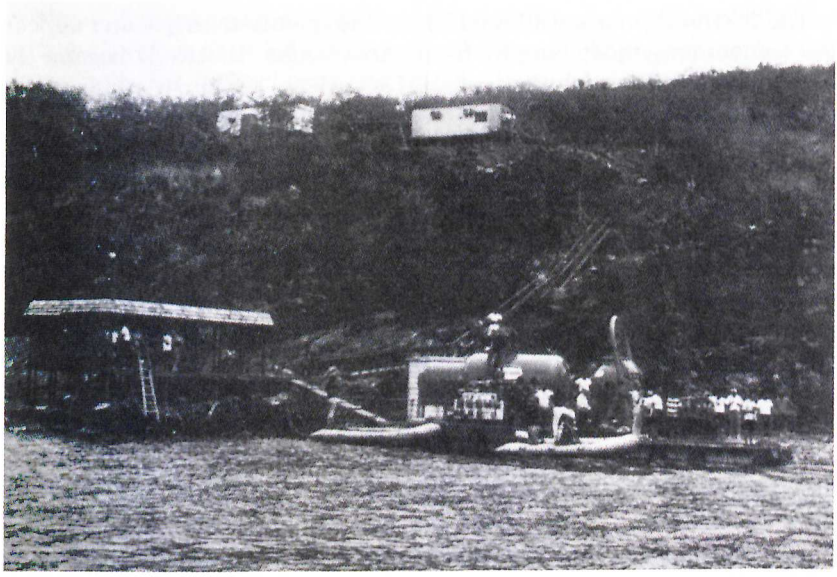

Figure 4-23. Shore-based support facilities for Tektite II. (*Photo by Ian Koblick.*)

The operational site for Tektite II was the same as for Tektite I. The principal difference was the arrangement for shore-based support in place of the barge-mounted systems used in Tektite II. Living accommodations for support personnel were in the same base camp as before (Fig. 4-21).

The habitat arrived from Philadelphia on a navy ship on March 7, 1970. For the next 12 days, preparations were made for emplacing the habitat on the seafloor, again at the saturation depth of 43 feet (13.1 m). The program immediately ran into what seemed an insurmountable obstacle: due to the lack of lifting devices, 80 tons of steel punchings had to be loaded by hand into the ballast compartments. This mammoth job was completed with the application of old-fashioned muscle power and on March 19, the emplacement was accomplished (Miller, VanDerwalker, and Waller, 1971). The rest of the system components were received, installed, and checked out during the next 2 weeks. To facilitate assembly, the decompression barge was made ready on the nearby island of St. Thomas.

The system finally was assembled and completely checked. On April 4, 1970, at 1:30 P.M., the five aquanauts entered the habitat to begin the first mission. The crew was composed of four marine scientists and the habitat engineer who was added based on the lessons learned in Tektite I. The breathing mixtures used in Tektite II were the same as those used in Tektite I: 92% nitrogen and 8% oxygen.

The Tektite II program allowed 53 marine scientists to live and work on the seafloor for periods ranging from 2 to 4 weeks. Tektite II became the first real underwater laboratory (VanDerwalker, 1971). In addition, the overall program offered training and education opportunities to over 360 university students. Thirty diving technicians from Highline Community College, Seattle, Washington, received months of experience as support divers as part of their two-year training program in commercial diving. About 35 psychology students from the University of Texas received training in field data collection and analysis techniques. In addition to the aquanauts, the Tektite II program provided an open-sea training school for some 296 student ocean science technicians working from an oceanographic research vessel. These programs and their results are described in Miller, VanDerwalker, and Waller (1971).

One unique feature of Tektite II was the inclusion of an all-female aquanaut team. Members were selected in the same manner as other aquanauts with respect to diving experience, scientific training, and physical condition. They performed admirably in carrying out their scientific mission, using the equipment, and maintaining the habitat (Earle, 1971). No problems were noted either medically or otherwise to separate female aquanauts from their male counterparts. Their fine per-

formance paved the way for the routine inclusion of female aquanauts in future undersea missions.

The knowledge gained from Tektite I made it possible to reduce the amount of effort spent on medical and engineering studies and to concentrate on biological and geological seafloor missions, crew behavior, and related ocean science programs conducted on the surface. Much was learned by the aquanauts beyond the specific scientific studies. In almost every instance, they would have liked to stay longer and expand on their work. Perhaps more important, all aquanauts experienced a changed perspective as a result of their ocean floor habitation. Many felt that if only they had known what it was really like, they could have planned their program better.

The decompression schedule was the same as that used for Tektite I. Because of bends symptoms reported by three members of the mission 2 team, however, the schedule was modified for the remaining missions. The original schedule required 19 hours and 22 minutes, including breathing oxygen, for 4 hours and 25 minutes. The modified schedule was 20 hours and 22 minutes and required 5 hours and 35 minutes of oxygen (Miller, VanDerwalker, and Waller, 1971). Use of the modified schedule for the other forty eight aquanauts resulted in only one case of pain-only bends.

The fifty three aquanauts including the author (Koblick) lived in the habitat for periods of 2 to 4 weeks without any significant medical problems. As in many previous programs, the most common malady was swimmer's ear. A detailed description of the medical program for Tektite II may be found in Beckman and Smith (1972).

The initial plan for Tektite II called for development and fabrication of a small, mobile two-person habitat (Minitat) with a depth capability of 100 feet (30.1 m). The objective was to overcome the limited mobility of a large, fixed habitat. An additional incentive for this development was provided by the speculation of several physiologists that saturation diving with nitrogen-oxygen mixtures should be possible to depths in excess of 100 feet (30.1 m). If this proved to be true, it would render large portions of the shallow continental shelf accessible to exploration and study through in situ techniques, without resorting to the more expensive and complex problems associated with helium-oxygen breathing gas mixtures.

In preparation for this part of the Tektite program, studies were conducted to develop new decompression tables for nitrogen-oxygen exposures to a depth of 100 feet (30.1 m). As a result of these studies, the schedule for decompression from saturation at 100 feet (30.1 m) adopted by the Tektite II Medical Board called for 49 hours and 20 minutes, including 2 hours and 50 minutes of oxygen breathing (Miller, VanDerwalker,

and Waller, 1971; Beckman and Smith 1972). This schedule was tested successfully in the laboratory but was not used in Tektite II because of operational problems. While lack of funds prohibited experimentation to establish a treatment program for accidental surfacing from 100 feet (30.1 m), the consensus of the medical board was that an aquanaut might be repressurized and treated if the surface interval lasted no longer than 3 minutes. Accordingly a treatment schedule was developed for use in emergency or accidental decompression from saturation at 100 feet (Beckman and Smith, 1972).

The Minitat was designed and fabricated during 1969 and early 1970 (Fig. 4-24). It was a 8 × 11 foot (2.4 × 3.4 m) vertical cylinder mounted on a pontoon catamaran, which provided flotation during surface transportation as well as providing a self-raising and -lowering capability. A 9 × 9 foot (2.7 × 2.7 m) ambient pressure wet room with a 42-inch (106 cm) entrance was connected to the underside of the pressure vessel and slightly recessed in the deck of the catamaran. Primary services, such as power, atmospheric gas, and fresh water, were supplied from the surface-support vessel.

In June 1970, the Minitat was towed to Lameshur Bay for crew training and system checkout. It proved unstable because of a shift between the

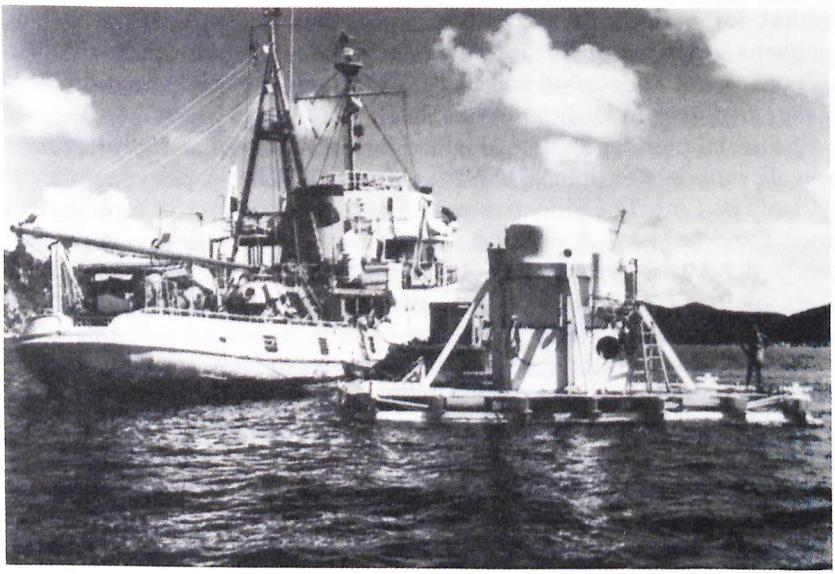

Figure 4-24. Minitat habitat with surface-support vessel *R/V Undaunted*. (*Official Department of the Interior photograph.*)

center of gravity and the center of buoyancy when passing through the air-water interface. This resulted in the Minitat's assuming a 45° angle during initial lowering, although once submerged, it righted itself (Fig. 5-28). Several weeks were spent attempting to rectify this problem by adding weight, shifting ballast, and other measures. Finally, after a series of mishaps, highlighted by the night the habitat broke loose in a storm and was discovered the next day being towed behind a native fishing boat, time ran out and the 100-foot (30.1 m) program was cancelled (Miller, VanDerwalker, and Waller, 1971).

Although the Minitat part of the program had fallen victim to technical gremlins, overall Tektite II was a successful effort. Table 4-4 summarizes the programs carried out during the 7 month program. The eleventh

TABLE 4-4. Summary of Tektite II Scientific Programs

Marine Science	*Psychological*	*Medical*
Biology		
Fish behavior in relation to experimental traps	Crew behavior in small spaces	Medical support program
Population dynamics of the spiny lobster	Habitability and life support features	Decompression table development
Bioacoustical studies of marine organisms	Effect of two-way closed circuit TV on behavior	Chronic nitrogen exposure study
Influence of herbivores on marine plants	Development of field data collection procedures	Microbiological monitoring of aquanauts and habitat atmosphere
Biology and behavior of fishes and crabs		
Effects of pollution on coral reefs		
Marine biochemistry and metabolic studies		
Geology		
Sea level history		
Bioturbation and sediment transport		
Underwater photography		
Comparison of cameras		
Study of dome corrector and flat port optics		

Source: Based on information in J. Miller, J. VanDerwalker, and R. Waller, 1971, *Tektite II Scientists in the Sea*, Stock No. 2400-0682, U. S. Department of the Interior, Govt. Printing Office, Washington, D.C.

and final mission was completed on November 6, 1970. The details of each Tektite II program are described in Miller, VanDerwalker, and Waller (1971).

On completion of the program, the habitat was returned to the Philadelphia Naval Shipyard, where it remained until November 1976. At this time the habitat was donated by the General Electric Company to Project Tektite, a nonprofit organization in California created for the purpose of fostering marine science and education. The habitat was transported to California, arriving there in January 1977. Since that time it has been undergoing refurbishment for use in the San Francisco Bay region.

CHERNOMOR, 1968–1974

About the same time Hydrolab I was being constructed in 1966, scientists in the Soviet Union were expanding their studies of underwater living and hyperbaric physiology. Between 1966 and 1971, ten Soviet underwater habitats were built. The Chernomor program represented the most extensive and advanced of these efforts (Podrazhanskiy, Rostarchuk, and Stefanov, 1973).

The Chernomor program was conducted in Moscow under the auspices of the Institute of Oceanology. Under the overall direction of Dr. Igor Mikhaltsev, deputy director of the institute, the Chernomor I habitat was completed in 1968. The chief designer of the habitat was Paval Borovikov. The Chernomor habitat was to serve primarily as a test platform and was used for a series of engineering studies in Golubaya Bay near Gelendzhik on the Black Sea. During this period, aquanauts were selected and trained, the ocean-floor scientific program developed, and baseline ecological data collected. A surface-support facility mounted on a 16.4 × 69.5 foot (5 × 21.2 m) pontoon catamaran was prepared. It contained power, air, supplies, and the communications systems, as well as a decompression chamber and medical support. Backup facilities on shore included a second decompression chamber, air compressors, and additional laboratories (Aybulatov and Yastrebov, 1973).

The basic pressure vessel was a cylinder 9.5 × 26 feet (2.9 × 7.9 m) with a depth capability of 164 feet (50 m) and a total system displacement of 62 tons (Podrazhanskiy, Rostarchuk, and Stefanov, 1973) (Fig. 4-25). The habitat had five 8-inch (20.3 cm) portholes and general accommodations for a crew of four or five. The life-support system was designed with the goal of maximum self-sufficiency on the seafloor. The aquanauts were able to control submergence, emplacement, surfacing, and decompression without assistance from the surface-support crew.

A series of missions took place beginning on July 18, 1968, during which twenty-eight aquanauts, formed into five teams, spent from 4 to 6

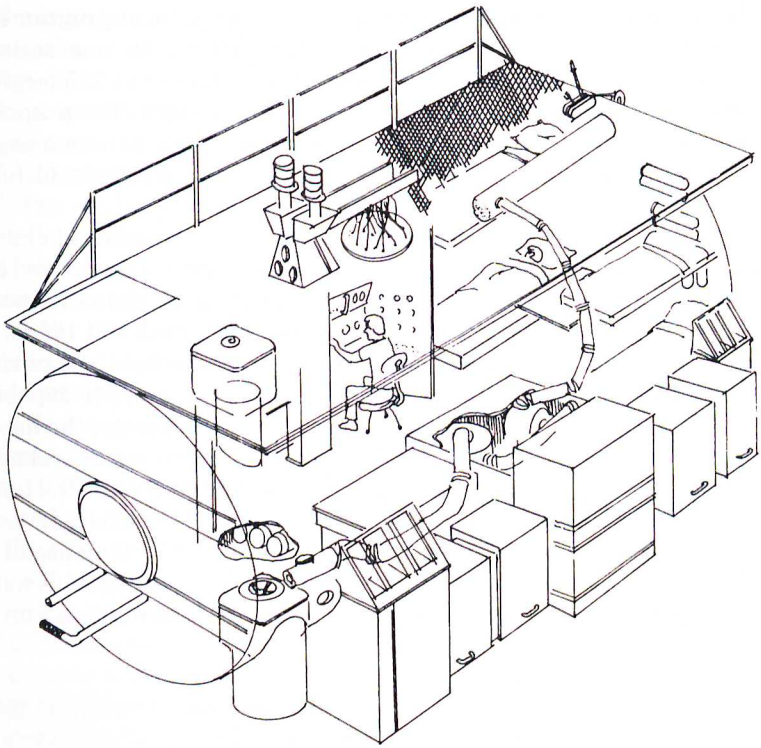

Figure 4-25. Chernomor I habitat. (*After P. Borovikov, V. Ivanov, and G. Obdirkin, 1969, Chernomor, Zemlya i vselennaya* ***2****:63.*)

days on the seafloor at a depth of 41 feet (12.5 m). The breathing gas in the habitat was air pumped from the surface. A careful study was made of the habitat atmosphere during which the oxygen content (averaging 17%) was tested every 4 hours (Borovikov, 1973). Routine measurements were made every few hours for carbon monoxide, carbon dioxide, and other trace contaminants. In addition to evaluating the habitat and its crew, objectives of these missions were to conduct biological, geological, and oceanographic studies. One of the major studies had to do with measurement of light polarization under water. Chernomor 1968 lasted about 1 month. Daily excursions were made averaging from 4 to 9 hours in the water per aquanaut, significantly more in-water time than in any previous habitat program. Most excursions used scuba, and descending excursions were made to depths of 295 feet (90 m) using air. Information is not available as to whether the dives to this extreme depth using air resulted in any incidents of oxygen toxicity.

The Chernomor program was preceded by other habitat programs and by laboratory experimentation (Grinevich, 1975). In one series of experiments, men spent 11 days in a pressure chamber at 165 feet (50.3 m) breathing a mixture of 13% oxygen and 87% nitrogen. The purpose of these experiments was to extend bottom time using nitrogen-oxygen breathing mixtures and to develop criteria for the selection of future aquanauts.

As a result of the Chernomor program in 1968, a number of changes were made in the habitat. The resulting habitat system was referred to as Chernomor II (Fig. 4-26). Chernomor II, 12 tons heavier than Chernomor I, displaced 74 tons. Battery capability was increased 100 times, gas supplies by a factor of 50, and the freshwater tanks held six times as much as did the original habitat (Borovikov, 1971). The depth capability now was 115 feet (35 m). As a result of these improvements, the habitat was capable of remaining independent of the surface for 2 weeks at a depth of 98.4 feet (30 m) in water temperatures of 64.4°F (18°C). Humidity within the habitat was maintained within a range of 75 to 85%, and temperature was between 77° and 80°F (25° to 27°C). Because of the problems associated with bad weather in previous missions, this autonomy was regarded as an important advantage. A deck mounted on top

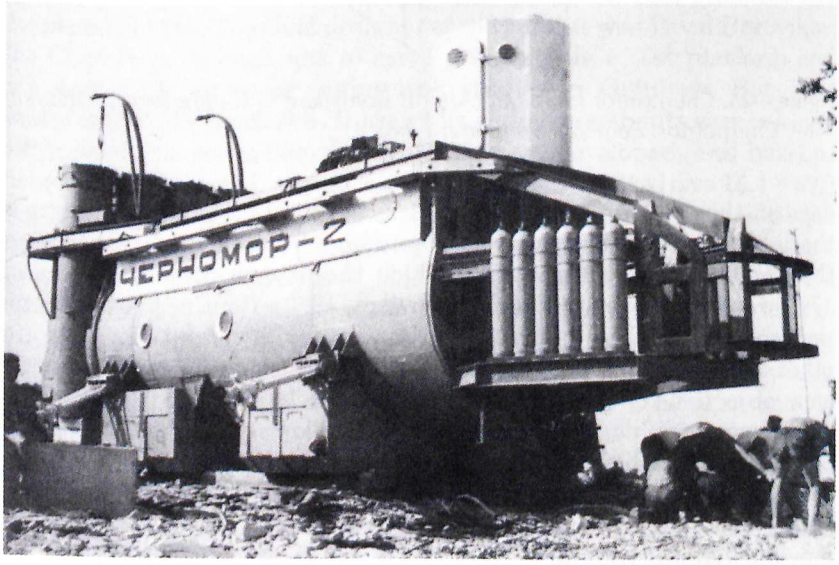

Figure 4-26. Chernomor II habitat. (*Courtesy of Institute of Oceanography Varna, Bulgaria.*)

of the pressure hull carried the mast, penetrators, air lines and communication cables, an escape hatch, and a PTC.

Figure 4-27 shows a schematic view of the habitat. Chernomor II was divided into three compartments: diving, living, and service. The diving compartment contained the entry hatch, the control panel, storage shelves, and a telephone. The living compartment was subdivided into a bedroom with two double bunks and a laboratory. The service compartment held the toilet, shower, and freshwater storage tanks.

At the time Chernomor II was built, it was anticipated that a number of similar habitats would be constructed for placement in the Baltic and in the Far East. It was thought that they could be used for harvesting such seafood delicacies as oysters, crabs, sponges, shrimp, and trepangs.

In 1969, the newly modified Chernomor II was used for the first time when five men spent 15 days at a depth of 49.2 feet (15 m). This was followed by a second 15-day mission at 82 feet (25 m). The breathing mixture in this latter mission was 88% nitrogen and 12% oxygen, which exposed the men to a significantly higher oxygen partial pressure than did Tektite, where at a saturation depth of 42 feet the mixture contained only 8% oxygen.

During this mission, it was found to be impossible to maintain the temperature inside the habitat within the desired limits because of the low outside water temperature and the underpowered heaters. When the water temperature decreased to 46.8° to 53.6°F (8.2° to 12°C), the inside temperature dropped to a chilly 57.2° to 59°F (14° to 15°C). As a result, the aquanauts had to put on all available clothing, became depressed and

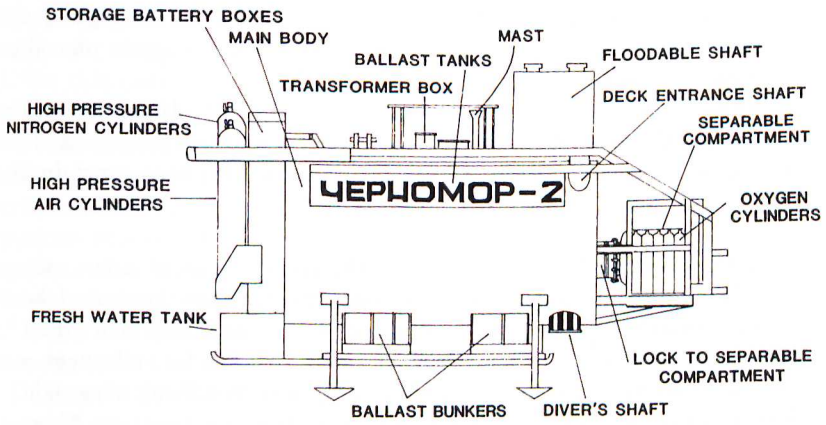

Figure 4-27. Layout of Chernomor II habitat. (*Courtesy of Institute of Oceanography, Varna, Bulgaria.*)

irritable, developed cold symptoms, and generally performed very poorly (Grinevich, 1975).

In 1970, two additional missions were conducted using the Chernomor habitat. The first took place from July 7 to 9 at the surprisingly shallow depth of 26.2 feet (8 m) during which the five-man crew tested the new life-support systems and other modifications made following the 1969 program. From August 6 to 10 a second mission was carried out at a depth of 101.7 feet (31 m) for further tests and evaluation.

In 1971, five men lived in Chernomor II for 52 days at a depth of 49.5 feet (15 m). Other than the 60-day mission during Tektite I, this was the longest time humans had lived on the seafloor. Prior to starting this mission, a crew of five aquanauts lived in the habitat at a depth of 39.4 feet (12 m) for two short missions from July 11 to 14 and from July 20 to 25 for the purpose of checking out the habitat. The 52-day mission began on August 1 when three aquanauts entered the habitat. The fourth aquanaut entered on August 8. On September 1 it was necessary to bring the habitat to the surface to lock out one of the four aquanauts and transfer him to shore because of illness. He was replaced by a new aquanaut on September 3. On September 15 a fifth aquanaut entered the habitat and remained with the crew until September 20 when the mission had to be aborted because of bad weather. The severe and rather exciting problems faced during this mission abortion are discussed in detail in Chapter 8. The breathing gas during this long mission was 16 to 17% oxygen and 83 to 84% nitrogen for the first 43 days and 11 to 12% oxygen and 88 to 89% nitrogen for the final 12 days (Klissurov, pers. commun.). The same breathing mixture was used both in the habitat and for diving, which differs from Tektite, where air was used for diving. Inside temperature was maintained at about 80°F (27°C). Extensive biological and geological experiments were carried out, with emphasis again placed on hydro-optical studies of light transmission.

There was considerable interest in the psychological adjustment of the aquanauts to the long confinement. The concern and the results can best be expressed by quoting one of the aquanauts who took part in the mission.

> The psychological problems caused by the confinement of a few men together for long periods of time was of great concern before the start of the project. Under these conditions, it is well known that men may tend to find fault with each other, that a man's silence may be taken for sullenness, a very neat man may be accused of being trivial; and it is difficult to say if in reality he did become trivial, or if it only seems that way to others. There were a few problems aboard the Chernomor during the first few weeks, but soon the crew came to fully appreciate the abilities of the other members, and no new problems arose. (Nikolayev, 1971, p. 4)

Because this mission was the second longest ever carried out, it is worth noting the results of some of the medical examinations. During the first few days of the mission, suppression of trigeminal and olfactory sensitivity were noted. After the first 5 to 7 days, the timbre of the voice changed. By the thirteenth day, all aquanauts complained of obstruction, pains, and buzzing in the ears, and there was a discharge in the outer auditory passage in two aquanauts. Examination showed that three aquanauts had dermatitis with a tendency toward eczema and that the other aquanauts had acute serous otitis and/or bilateral serous otitis (Shaparenko, Zhurba, and Grinevich, 1975). Shaparenko and his colleagues also found inflammation in the mucosa of the nose, pharynx, and larynx and an impairment of hearing. Changes in ear, nose, and throat conditions were found to be cyclic and a function of the diving schedule and alterations in the habitat atmosphere. All of these disturbances regressed within 2 to 7 days following decompression.

The summer of 1972 saw a continuation of the Chernomor program, with several missions being carried out. A typical crew was composed of two or three scientists, a habitat engineer, and a professional diver. Most excursion diving used a hookah (air hose) system with scuba backup. Extensive physiological studies were carried out during all of the Chernomor programs (Kolchinskaya et al., 1976).

From June 25 to July 3, four aquanauts lived in the habitat at depths ranging from 16.4 to 42.6 feet (5 to 13 m) for the purpose of crew system training. On August 4 the habitat was placed at a depth of 98.4 feet (30 m) where it was entered by a crew of five aquanauts on August 8. This team remained on the seafloor until August 29, when they were transferred to the surface in a PTC for decompression.

Following the successful completion of this 21-day mission, the habitat was made ready for the next mission, scheduled to begin on September 11. On this date a crew of four aquanauts entered, where they remained until October 5, having been joined by a fifth aquanaut on September 29. The decompression of the five aquanauts took place in the habitat on the seafloor instead of on the surface as it had for the previous team (Klissurov pers. commun.). The breathing mixture for the two 98.4-foot (30 m) missions was 5 to 8% oxygen and 92 to 95% nitrogen, the same mixture used later for the La Chalupa missions conducted at 100 feet (30.1 m). Water temperatures during these programs ranged from 39.2° to 73.4°F (4° to 23°C). This completed a busy season during which 240 man-days were spent on the seafloor.

During the period 1969 to 1972, test crews and scientific teams amassed a total of 4,000 man-hours in the Chernomor habitat. The average time in the water was 4 to 6 hours a day (Stefanov, 1972). Decompression, which usually was accomplished within the habitat, did not involve the use of oxygen and required 19 to 20 hours from a depth of 49 feet (15 m), 32

hours from 65.6 feet (20 m), and 42 to 49 hours from 98.4 feet (30 m). The decompression times for the 49- and 98.4-foot missions are basically the same as those developed for Tektite, except that the Soviets did not use oxygen.

In 1973 and 1974, Chernomor II was used in two programs, both in a protected bay on the Black Sea at Cape Maslen, near Burgas, Bulgaria. The programs were cooperative efforts with Bulgarian scientists and engineers from the International Underwater Research Center in Varna, Bulgaria, conducted through auspices of the Council for Mutual Economic Aid (SEV). They involved over 100 persons each year from the USSR, Bulgaria, and the German Democratic Republic.

The operational site was about 650 to 1000 feet (200 to 300 m) from shore at a depth of about 60 feet (18.3 m). Life support was provided both from a shore base and a support ship in the same manner as in the earlier Chernomor missions (Fig. 4-28). The ship carried the decompression and communication systems. Divers breathed a mixture of 90% nitrogen and 10% oxygen, a slight decrease in oxygen from earlier missions.

The 1973 mission took place from July 7 to 23. Diving excursions again used hookah systems with scuba backup. Descending excursions of any consequence were not possible because the depth was only 80 feet (24.4 m) out to a distance of 650 feet (198 m) from the habitat. After their 14 days on the seafloor, during which they spent 61 hours in the water, the aquanauts underwent 33 hours of decompression, thus completing the 1973 program.

The 1974 program took place from July 14 to August 2, with the last two days in decompression. During the 16 days on the bottom, the aquanauts spent 67 hours in the water with temperatures ranging from 46.4° to 62.2°F (8° to 19°C).

The scientific program of these two missions in Bulgarian waters included experiments on underwater light transmission, basic oceanographic studies, fisheries studies in which trout from a freshwater Bulgarian lake were transferred to seawater, and physiological studies on the aquanauts involving pulmonary, cardiovascular, and electroencephalographic measures. Additional studies involved the comparison of diving equipment including the test of diver heating and breathing systems.

As was the case with other habitat programs, the Chernomor aquanauts found their equipment to be a constant problem, requiring much attention and repair. Also the habitat turned out to be considerably underballasted and was only 4 tons negative on the seafloor. As a result, on one occasion the habitat tipped up to an angle of 30° to 40° with men inside. Another time it was lifted and bounced across the bottom until it ended up in the surf zone.

Considerable effort was expended to make the habitat comfortable.



Figure 4-28. Surface-support facilities for Chernomor II at Cape Maslen, Bulgaria, 1973 and 1974. (*Courtesy of Institute of Oceanography, Varna, Bulgaria.*)

Comforts included hot water, carpets, a colorful decor, TV, and an adequate drying area designed to minimize dripping water in the living quarters.

According to Nikolaev and Yastrebov (1978, p. 13), "The principal results of the Shelf-Chernomor program derive from the organizational successes from an international collaboration standpoint and the refinement of techniques for conducting complex underwater research from an MUL (Manned Underwater Laboratory) base." The total number of participants in the 1973 and 1974 Chernomor programs were 112 and 104, respectively.

The Chernomor II habitat has not been used since 1974 and has remained at a shipyard in Burgas, Bulgaria since then. Long months in the sea took their toll, and Soviet and Bulgarian engineers decided the hull no longer was safe because of rusting and pitting of the metal.

SEATOPIA, 1968–1973

The undersea activities in France and the United States in the early 1960s stimulated the interest of scientists and engineers in Japan. In 1965 the Science and Technology Agency of Japan provided a grant for comprehensive studies of the recent advances in the field of diving with the intention of launching similar experiments in Japan. Using this grant, a group of scientists of the Tokyo Medical and Dental University conducted a successful chamber saturation diving experiment in 1967 to a depth of 328 feet (100 m). In 1968, the agency contracted with the Japan Association of Underwater Exploitation to perform an engineering study and to construct an undersea habitat system. The system was to consist of the habitat, a support ship equipped with a decompression chamber, and a PTC.

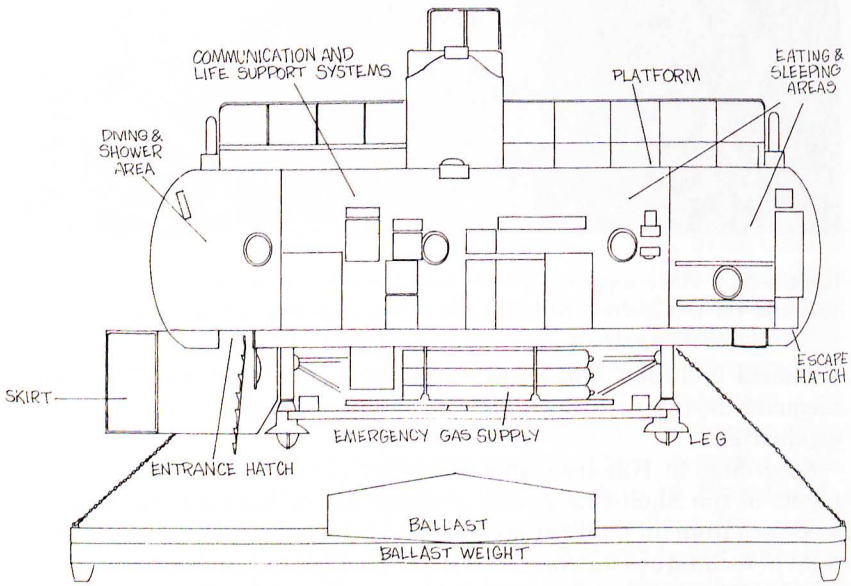

Figure 4-29. Schematic of Seatopia habitat. (*Courtesy of Japan Marine Science and Technology Center, Yokosuka, Japan.*)

The construction of the three principal components of the system was completed in 1969. The habitat, designed to house a crew of four, was a 7.5 × 34.6 foot (2.3 × 10.5m) cylinder weighing 65 tons. Seatopia had many of the same features as previous habitats, including an electrowriter for communication to the surface, eating and cooking facilities, an entertainment TV, and the necessary life-support functions (Fig. 4-29). The PTC consisted of a 5.7 × 9.3 foot (1.7 × 2.8 m) pressure hull (Fig. 4-30). The support ship, constructed especially for the Seatopia program, is shown

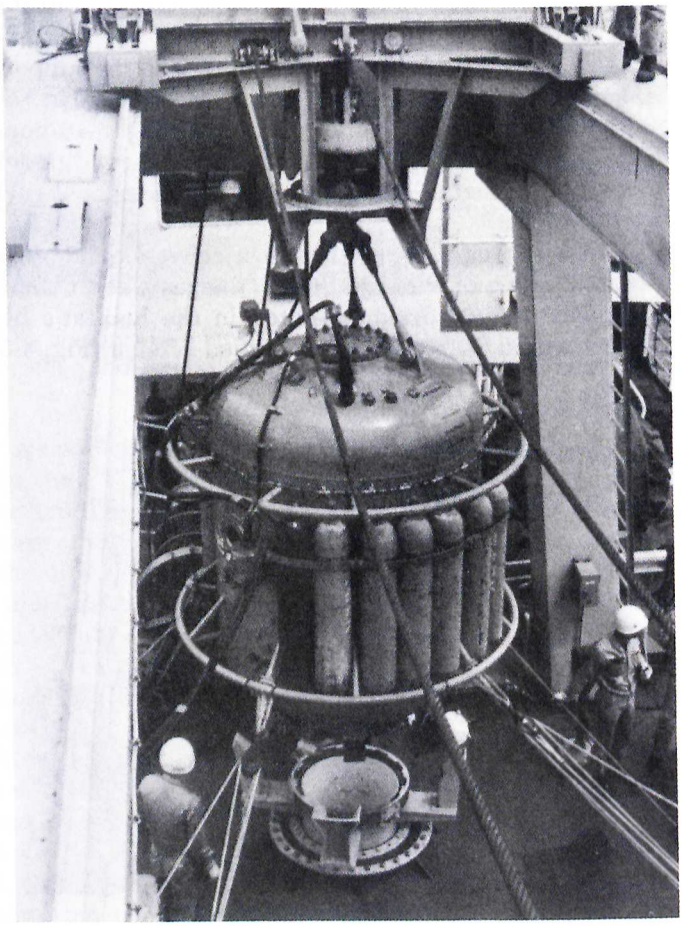

Figure 4-30. Personnel transfer capsule used in Seatopia habitat program. (*Courtesy of Japan Marine Science and Technology Center, Yokosuka, Japan.*)

in Fig. 4-31 with the PTC on board, moored in Yokosuka Harbor. This is the only habitat program known to us in which a new surface-support vessel was provided; all other programs found it necessary to use available vessels.

During 1970, the Seatopia program came to a standstill due to governmental reorganization. Finally in 1971 the newly formed Japan Marine Science and Technology Center (JAMSTEC) took over the program with the intention of conducting further tests (Matsuda, 1972). It was at this time that the program was christened Seatopia. Two habitat missions were planned, one at 98.4 feet (30 m) and the second at 196.8 feet (60 m), which would lead to the ultimate goal of four aquanauts living at a depth of 328 feet (100 m) for 1 month.

In 1972, a simulation dive was carried out on board the support vessel moored in the shipyard of the Maritime Self-Defense Force in Yokosuka. Four divers stayed at a depth of 132 feet (40.2 m) for 46 hours. The breathing mixture was 7.5% oxygen, 28.2% nitrogen, and 64% helium. The test was carried out successfully, and the divers emerged following a 29-hour decompression.

Also in 1972 the habitat underwent a major conversion in preparation for open-sea trials. One of the significant changes was in the method of ballasting. The original design resulted in the habitat's having a severe list much as did Sealab II. The modified version (Fig. 4-32) now

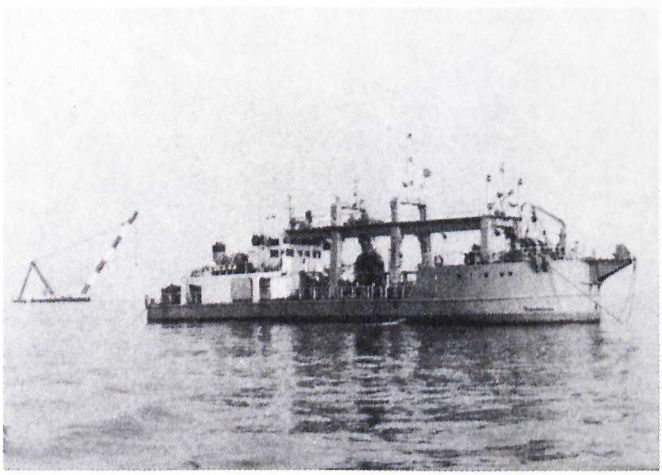

Figure 4-31. Support ship used for Seatopia program following conversion in 1972. (*Courtesy of Japan Marine Science and Technology Center, Yokosuka, Japan.*)

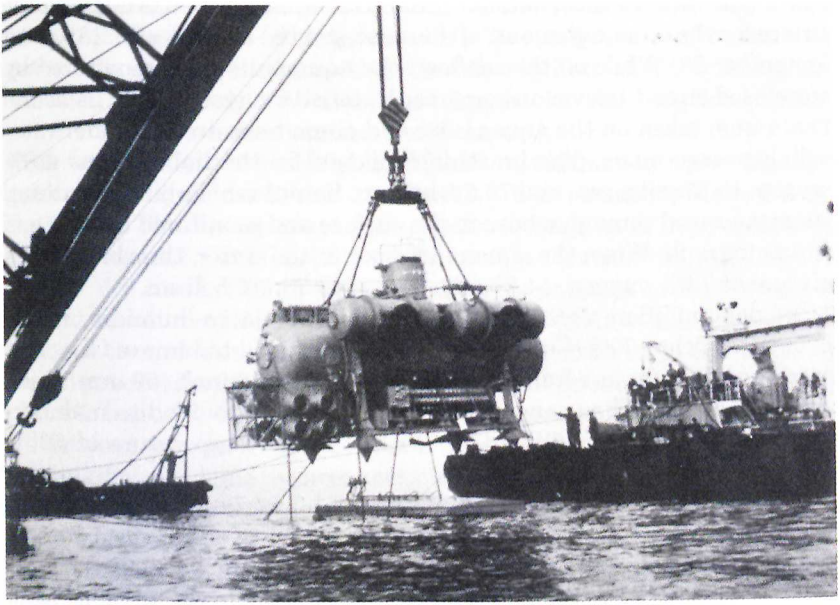

Figure 4-32. Seatopia Habitat following conversion in 1972. (*Courtesy of Japan Marine Science and Technology Center, Yokosuka, Japan.*)

greatly resembled Sealab III. Modifications were made during this period to the PTC, and a center well was added to the support ship to facilitate handling at sea.

A series of saturation diving experiments was commenced in 1971 under the direction of JAMSTEC. These studies continued into 1973, ending in August 1973 when four divers and a physician lived in the DDC on board the habitat support ship for 168 hours at a simulated depth of 231 feet (70.4 m). The study went smoothly, and the divers completed the saturation safely following the 71-hour decompression.

Seatopia's first and only open-sea mission took place in September 1973. Preparation began in April with the training of aquanauts, checking out the various systems, and simulated chamber tests. Port Tago, on the southeast coast of Japan near Yokosuka, was the site selected. The habitat was placed on the seafloor at a depth of 98.4 feet (30 m) on August 9, 1973. On September 22 the four aquanauts entered the DDC at 2:00 P.M. where they compressed over a period of 2 hours and 40 minutes to the saturation depth. This procedure differed from other habitat programs where compression was achieved in the habitat itself. The aquanauts remained in the deck chamber until 10:30 the following morning at

which time three of them entered the PTC. Following a return trip to the surface for the other aquanaut, all four entered the habitat at 3:25 P.M. on September 23. While on the seafloor, the aquanauts were monitored by four closed-circuit television cameras. Extensive physiological measurements were taken on the aquanauts, and some measures of underwater visibility were made. The breathing mixture in the habitat was 4.8% oxygen, 16.0% nitrogen, and 79.2% helium. Samples of habitat breathing gas were passed through a hose to the surface and monitored using a gas chromatograph. When the aquanauts were in the water, they breathed a mixture of 7.2% oxygen, 14.2% nitrogen, and 78.6% helium.

Two dehumidifiers were used to maintain the relative humidity inside the habitat below 70%. Lithium hydroxide was used to remove CO_2. The interior of the pressure hull was insulated with 0.16-inch (50 mm) thick cork board with radiant and electric floor heaters provided to maintain inside temperature at 86°F (30°), with a water temperature of 50°F (10°C).

At 11:35 A.M. on September 26, after 68 hours on the seafloor, the aquanauts entered the PTC and were transported to the surface decompression chamber, where they completed their 66-hour decompression.

Significant work has been done since 1973 relating to the advancement of saturation diving in Japan. A deep-diving simulation complex has been completed and used for several deep saturation dives, including a 1000-foot (304.8 m) dive in 1979. Seatopia is located at a shipyard in Yohosuka and there are no plans for using it for further undersea studies.

HELGOLAND, 1968–1976

By 1964, the work of Bond and Cousteau was quite familiar to German scientists at the Institute for Aviation Medicine in Bonn. Several experiments had been conducted in the institute's hyperbaric chambers, including at least one in which divers spent over 50 hours at a depth of 100 feet (30.5 m). These studies continued, and in 1966 two physicians spent over 100 hours at a depth of 721 feet (220 m). During that same year, the concept of an underwater laboratory (UWL) was developed and a preliminary design formulated. Dr. O. Kinne, director of the Biological Institute, Helgoland, was consulted in the early design stages. Over the next two years, the design was approved and a mockup of the habitat completed. In 1968, the project won official approval and construction began. The year 1968 was a banner year for the construction of habitats as Tektite, Sealab III, Chernomor, and Seatopia, as well as several smaller habitats were constructed.

By November 1968, the major system components of the UWL were

completed and assembled, and on July 7, 1969, the habitat was transported to Helgoland. The program officially was now a cooperative one between the Institute for Aviation Medicine in Bonn and the Biological Institute, Helgoland, with financial support for the program coming from the Ministry for Education and Science.

The main body of the Helgoland habitat, nicknamed the "pregnant elephant," is a cylinder 29.5 × 19.7 feet (9 × 6 m) divided into two rooms (Fig. 4-33). The living room (which also served as a decompression chamber) was 8.2 × 8.2 feet (2.5 × 2.5 m) and the machine room 8.2 × 21.3 feet (2.5 × 6.5 m). This compartment was capable of withstanding an external pressure of 328 feet (100 m). The UWL thus was designed to support a crew of four at depths to 328 feet for up to 3 weeks. The machine room also served as a wet room, an observation room, and a laboratory. Comforts included a kitchen, a toilet, a shower, and the necessary furniture for four people. A typical crew would consist of one professional diver-engineer and one to three scientists, the same crew composition the Soviets used in the Chernomor program.

Life support was contained primarily in an unmanned buoy on the surface, referred to as the energy station or the oil pigeon, connected

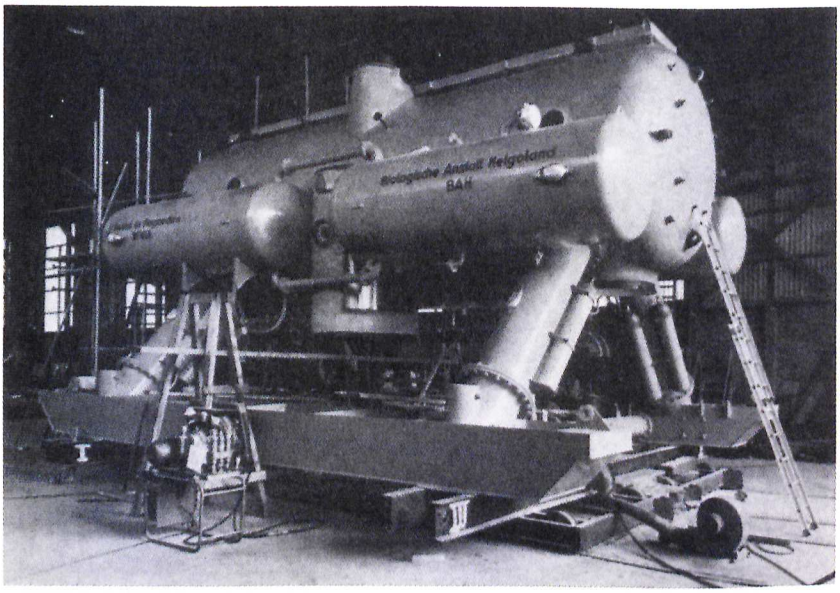

Figure 4-33. Helgoland underwater laboratory, 1969. (*Courtesy of Society for Nuclear Research in Ship-Building and Navigation, Bonn, Germany.*)

to the habitat by an umbilical that provided power, breathing gases, and communications to shore (Fig. 4-34). With the energy station functioning, the habitat could operate for up to 20 days without shore support. If it failed, the habitat had sufficient power, food, and breathing gases to be self-supporting for 10 days.

With the habitat operating in the usually adverse conditions of the



Figure 4-34. Life-support buoy for Helgoland habitat. (*Courtesy of Society for Nuclear Research in Ship-Building and Navigation, Bonn, Germany.*)

North Sea, special attention was given to the matter of ballast. While under tow, the UWL had a positive buoyancy of about 1 ton. Once on the seafloor, however, and the ballast tanks flooded, its negative buoyancy was 16 tons. Additional technical details of the UWL system are shown in Table 4-5.

The UWL had some unique safety features. A one-man rescue chamber located under an emergency hatch in the living room could be used to evacuate a sick or injured aquanaut to the deck chamber on the surface or to a shore station. A PTC also was available for evacuation. In major emergencies, aquanauts could decompress in the UWL and swim to the surface, which also was the normal means of decompression at the end of a mission. Included in the system was an underwater igloo that could be used as an emergency station, a discussion room, and for communication to the main habitat by aquanauts out in the water (Fig. 4-35). The igloo was equipped with lights, a CO_2 scrubber, emergency air, and a sonic pinger to aid in locating the habitat.

Table 4-5. Specification of the Helgoland Habitat and Energy Station

Total system		Wet room	
Operation depth	(328) ft		
Number of aquanauts	4	Length	15.7 ft
Supplying periods		Height	19.7 ft
Fuel	3 weeks	Base area	15.7 x 20.7 ft
Baralime	2 weeks	Weight in air	27 t
Breathing gas	2 weeks	Weight on the bottom	6 t
Fresh Water	3 weeks	Volume	706 ft^3
Food (emergency)	2 weeks	Windows of 19.7 inches in diameter	3
Maximum towing velocity	5 knots	Work tables	2
UWL main body		Energy station	
Length	29.5 ft		
Height	19.7 ft	Height	42.6 ft
Base area	31.2 x 20.7 ft	Diameter	9.8 ft
Draft	17.4 ft	Weight	13 t
Weight in air	75 t	Effective Power of the Diesel generator	25 kVA
Weight on the bottom	16 t	Delivery of the compressors	240 N1/min
Diameter of the cylinder	8.2 ft		
Volume of the cylinder	1483 ft^3		
Insulation			
PU foam/reinforced Polyester			
Relative humidity	70 to 80%		
Installed electric power	27 kW		
Voltages	12V=/24V=/220V-		
Capacity of emergency battery	2000Ah		

Source: After Anonymous, 1972, *Research and Experimentation in the Sea with Underwater Laboratory Helgoland,* Society for Nuclear Research in Ship Building and Navigation, Hamburg-Geesthacht, p. 8.

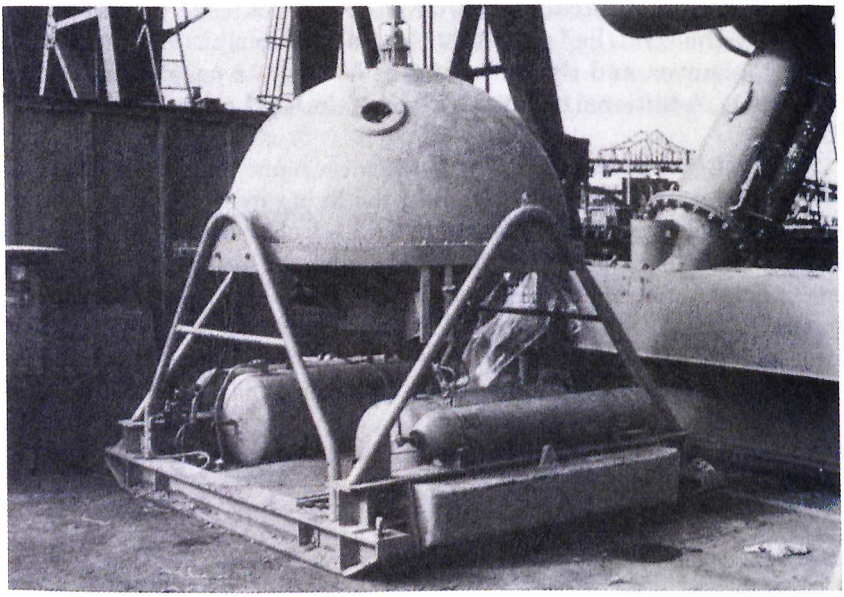

Figure 4-35. Emergency station for Helgoland habitat. (*Courtesy of Society for Nuclear Research in Ship-Building and Navigation, Bonn, Germany.*)

The Helgoland UWL carried out experiments in marine biology, geology, oceanography, and physiological and psychological studies of the aquanauts themselves. The first of three manned missions began on July 28, 1969, in the North Sea about 1.5 mile (2.4 km) from the island of Helgoland at a depth of 75.4 feet (23 m). Between July 28 and August 19 a total of eight aquanauts lived in the habitat in teams of two, three, and four. Two of the aquanauts later participated in Tektite II. Although the water temperature was a cold 41°F (5°C), the temperature inside the habitat was maintained at 64.4° to 70°F (18° to 21°C), with humidity ranging from 70 to 80%. The duration of the missions ranged from 5 to 11 days, with a required decompression time of 24.5 hours. The breathing mixture in the habitat was nitrogen-oxygen with a partial pressure of oxygen of about 0.35 ATA. Air was used for all diving excursions. This general practice was followed for all future Helgoland missions.

The primary objectives of these missions were to test the new habitat from an engineering and handling standpoint and to study the reactions of the aquanauts to exposure in a hyperbaric environment; thus, numerous medical and psychological tests were used. The scientists and engineers who participated considered this initial program to be a complete success. It demonstrated that the weather conditions in the Bay of

Helgoland did not present any limitation for a properly planned underwater station. Even in the rough northern areas, the operation of underwater habitats was felt to be profitable, both technically and scientifically. A complete account of the 1969 mission is contained in Ruff, et al. (1971) and Fust (1970). After a period of 9 months, the habitat was towed back to shore on April 4, 1970.

During 1971 the habitat was modified and overhauled and an 8 × 12 foot (2.3 × 3.6 m) wet room added (Fig. 4-36 and Table 4-5). Following this modification, which we will call Helgoland II, a mission was carried out in Lubeck Bay from August 28 to September 3, 1971. In 1972, technical responsibility for the habitat was transferred to the firm Gesellschaft fur Kernenergieverwertung in Schiffbau and Schiffahrt mbH (Society for Nuclear Research in Ship-Building and Navigation (GKSS).

The UWL was used from July 26 to September 10, 1973, again off the coast of Helgoland in the North Sea about 2 miles (3.2 km) offshore at a depth of 75 feet (22.9 m) where the water temperature was a cool 62°F (16.7°C). During this period, one of the objectives was to conduct a 4-day saturation mission to determine if the habitat would be suitable for use in the U.S. Northeast coastal regions. For this reason, U.S. scientists and engineers from the NOAA, the University of New Hampshire, and the

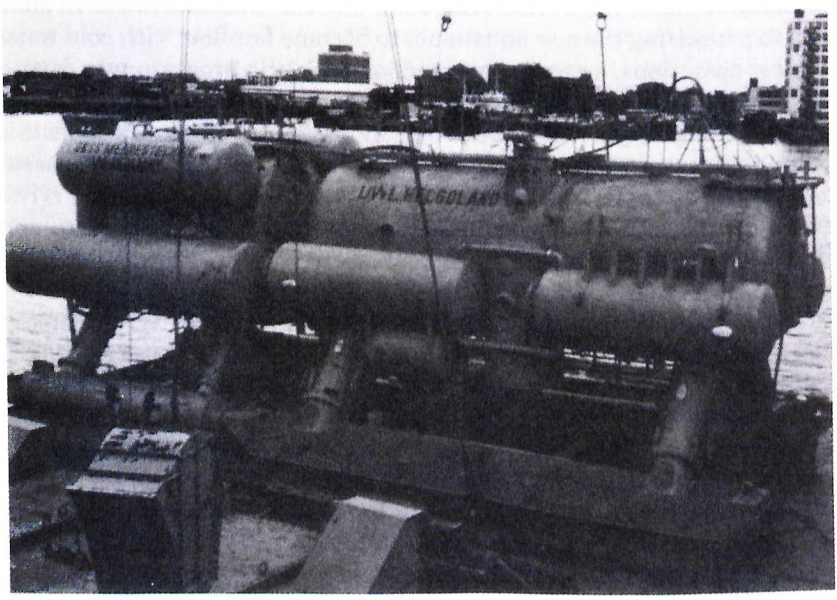

Figure 4-36. Helgoland underwater laboratory, 1971, (*Courtesy of Society for Nuclear Research in Ship-Building and Navigation, Bonn, Germany.*)

Woods Hole Oceanographic Institution participated both as surface-support divers and as aquanauts. The mission was divided into two phases. The first phase consisted of the U.S. team's becoming familiar with the UWL and its operation by assisting in its deployment and in making nonsaturation dives to the seafloor. The second phase was a four-day saturation with participants from West Germany and the United States. The program was accomplished safely, with the biggest difference between German and U.S. diving procedures being that the Germans did not use the buddy system and made untethered excursions from the habitat in poor visibility. In addition to evaluating the habitat, physiological measurements and biological observations were made by the aquanauts in water with visibility of about 3 to 7 feet (0.9 to 2.1 m). During this mission, the habitat humidity was about 70% and the inside temperature 79°F (26°C), which was important considering that the habitat was to be used in the cold waters off the coast of New England.

Between August and October 1974 the UWL was used again for a series of saturation dives. The habitat was located 1.5 miles (2.5 km) offshore from the town of Niendorf in the Baltic Sea at a depth of 50 feet (15.2 m). Water temperatures ranged from 43° to 59°F (5.6° to 15°C). This series of three 1-week missions was particularly interesting because the aquanaut teams were composed of engineers and scientists from Germany, France, the United Kingdom, and the United States. In addition to permitting the new aquanauts to become familiar with cold water habitat operations, an extensive seafloor scientific program was carried out. Over a period of 102 days, 24 aquanauts were saturated. Experiments included oxygen, metabolic demands and diurnal cycles of benthic communities, and controlled experiments concerned with photosynthesis, light levels, and water chemistry as these parameters affect the survival and the behavior of benthic animals (Manned Undersea Science and Technology, 1976). This program represented the most sophisticated scientific program yet carried out using the UWL habitat.

The largest UWL program took place in 1975 involving over 60 persons from Germany, Poland, the USSR, and the United States. The UWL habitat was transported from Germany to the United States aboard the Polish factory ship *Pomorze* in September 1975. During the third week in September, the habitat and support facilities were deployed at Jeffreys Ledge in the Gulf of Maine 8.5 miles (13.7 km) due east of Rockport, Massachusetts (Fig. 4-37). The saturation depth was 103 feet (31.4 m), the greatest depth at which the UWL had been deployed. The breathing gas in the habitat was a normoxic mixture of 93.6% nitrogen and 6.4% oxygen. A normoxic (normal oxygen) breathing mixture is one in which the partial pressure of oxygen at a specified depth is close to, or slightly above, the normal (surface) atmospheric value of 0.21 ATA (atmospheres

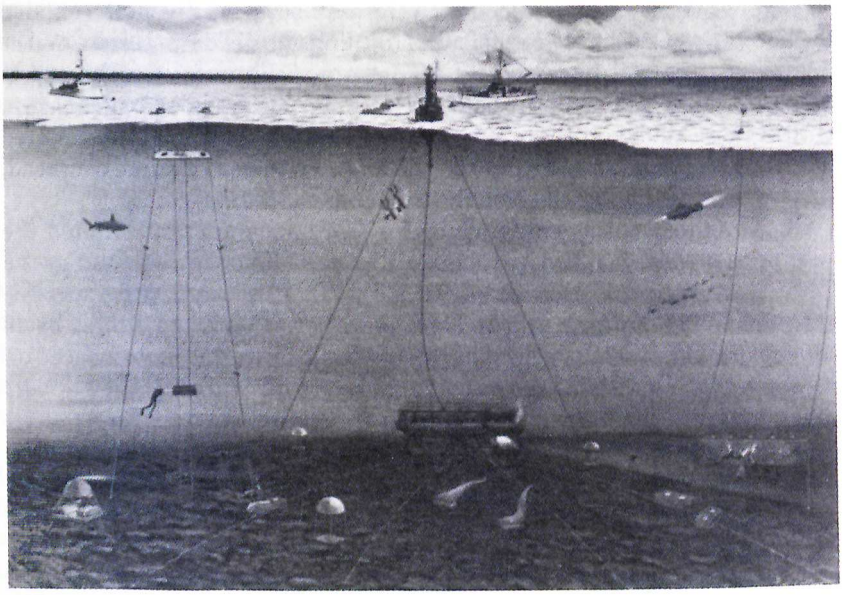

Figure 4-37. Artist's conception of Helgoland multinational program, 1975. (*Official National Oceanic and Atmospheric Administration photograph.*)

absolute). Water temperature varied from 45° to 53°F (7.2° to 11.7°C). The principal objectives were to conduct hydroacoustic experiments and to observe the spawning behavior of herring and the immediate posthatching behavior of herring larvae.

The original plan called for five 4-man teams to saturate for 2 weeks per team. Prior to beginning the first scientific mission, a short 2-day/2-night checkout mission was conducted by three German aquanauts beginning on September 21, 1975. On September 23 this team was joined by an American aquanaut sent down to assist in preparing the habitat for the first scientific team. On September 25, two of the German aquanauts completed decompression and returned to the surface. During this ascent, one of the German aquanauts, Joachim Wendler, died as a result of a massive air embolism. The subsequent board of inquiry determined that the accident was not the result of a failure of the system, and it was decided to continue with the program.

On September 26 the two aquanauts on the seafloor were joined by another American aquanaut. All three were evacuated the next day due to bad weather. It was not until October 3 that the first scientific team entered the habitat. This team completed a 2-week mission and surfaced

on October 20. They were joined by a German support diver who entered the habitat on October 17 to assist in handling the decompression, and he in turn was joined by a second German aquanaut on October 20 in preparation for the second scientific mission. Because of bad weather, both of these aquanauts were evacuated on October 24 when they reported that the habitat was moving on the seafloor due to heavy surge overhead, surprising considering the heavily ballasted system.

On November 6, an American and a German aquanaut entered the habitat to prepare for the second scientific team. They were joined by the other two members of the team on November 8. This 4-man team successfully completed their mission on November 19, which was followed by 49 hours of decompression in the habitat on the seafloor. All four surfaced on November 21. One of the American aquanauts on reaching the support ship experienced what was either central nervous system bends or an embolism; he was placed immediately into a two-man decompression chamber and transferred to shore where he was locked into a larger chamber. Although treatment was generally successful, some minor residual disability remains.

The New England program was plagued by problems of weather, equipment failures, tragedy, and almost a second tragedy. Whereas five scientific missions originally were scheduled, only two were carried out. In addition to the adverse weather conditions and the death of the German aquanaut, the scientific missions were compromised seriously because the herring did not spawn close enough to the habitat to be observed, and there were severe technical problems with the hydroacoustic array that prevented the planned experiments from being carried out.

The aquanauts averaged 1 hour and 20 minutes per day per aquanaut in the water, for a total of 215 hours of science-oriented water time (Manned Undersea Science and Technology, 1977). Excursions were made as far as 600 feet (183 m) from the habitat and to depths up to 150 feet (45.7 m). Diver propulsion units were employed during the saturation missions, and it was found that the variable-volume wet suits used kept the aquanauts warm for periods of up to 2 hours.

The UWL was transported back to Germany following the 1975 mission in the United States and from June 24 to July 31, 1976, was used again for missions with an international flavor. The dive site for the 1976 missions was in the Bay of Lubeck, Germany, 0.62 miles (1.0 km) offshore near Neustadt at a saturation depth of 52.5 feet (16 m). During this program four teams of four aquanauts each saturated for 7 days. Participating aquanauts were from West Germany, the United States, and France. The scientific objectives encompassed oceanographic studies, evaluation of diver-held measuring devices, and other diver equipment, including a digital diver communication system, a physiological telemetry

system, and a digital decompression meter (Manned Undersea Science and Technology, 1977). The Helgoland habitat was retired officially in 1979 and now is located on shore in Gestacht, a small town about 20 miles southeast of Hamburg, in West Germany.

AEGIR, 1969-1971

The Aegir habitat was built in 1969 for Makai Range, Inc., one of three affiliated companies under the direction of Taylor A. Pryor, the prime mover behind the development of a marine research center at Makapuu on the island of Oahu, Hawaii. The center consisted of Sealife Park (a profit-oriented marine life public park), the Oceanic Institute (nonprofit marine research facility), and the Makai Undersea Test Range.

Aegir (named for the Norse god of the sea), operated by Makai Range, Inc., was designed as a versatile, movable, seafloor research and test facility. The system was comprised of the habitat, a surface-support vessel, and a permanent shore-support facility (Fig. 4-38). Aegir consisted of a series of pressure chambers divided into living, control, and laboratory compartments mounted on a towable catamaran barge (Fig. 4-39). The living and laboratory compartments were identical in shape and size,

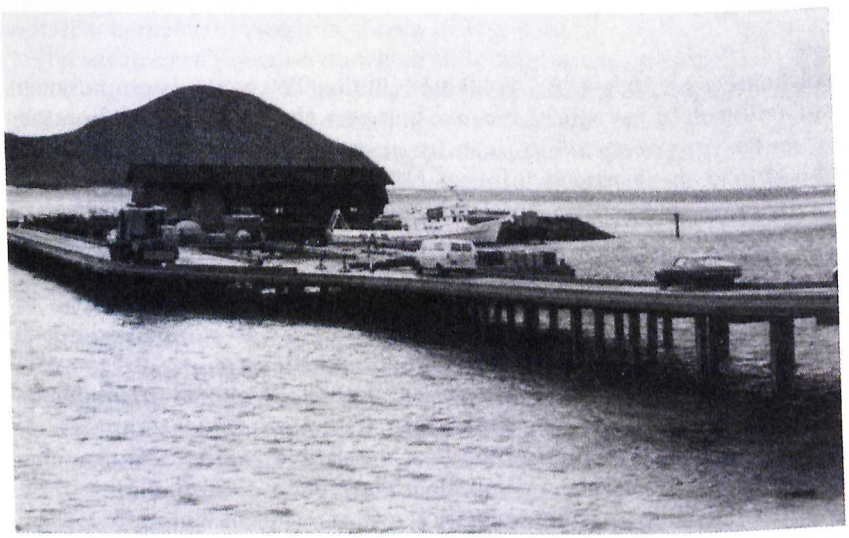

Figure 4-38. Makai Range support facility for Aegir habitat. (*Courtesy of Makai Range Inc., Honolulu, Hawaii.*)

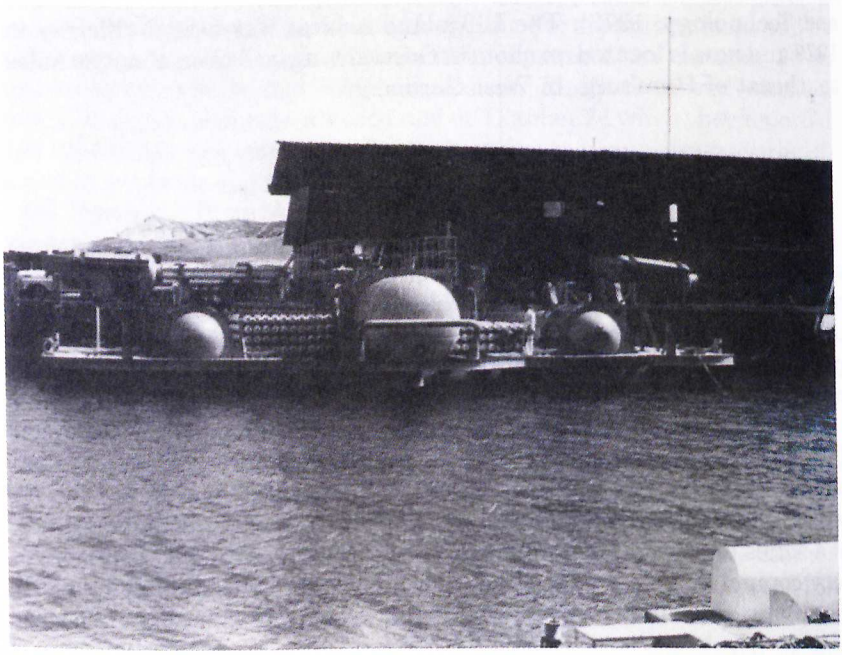

Figure 4-39. Aegir habitat at dock. (*Courtesy of David Adkins.*)

each being a 9 × 15 foot (2.7 × 4.6 m) cylinder. The control compartment was a 10-foot (3 m) sphere located between the living and laboratory compartments connected to them by passageways. Each chamber had from four to six viewports 6 inches (15.2 cm) in diameter and hatches that allowed them to be operated independently and pressurized to maximum depth from either side. While the chamber was on the surface, entry to it was through a 30-inch (76.2 cm) diameter hatch on top of the laboratory compartment. A bottom hatch located in each compartment permitted access to the water when the habitat was submerged. Each bottom hatch was surrounded by an outside skirt long enough to compensate for tidal changes. Further technical details are shown in Table 4-6.

The living compartment, which also was used for decompression, contained four wall-mounted bunks, a lavatory, a table, cabinets, plus storage space for two cots and supplies. The control chamber housed the buoyancy controls, the communication system, the control units for the mixed gas supply, a shower, and racks for hanging wet diving equipment. The laboratory compartment contained a counter with sink and cabinets, most of the electric and electronic equipment, and the galley, which was

Table 4-6. Specifications of the Aegir Habitat

Length	72 ft	Maximum depth	580 ft
Max beam	53 ft	Duration @ 580 feet	20 days
Full load draft	8 ft	Accommodations	6 aquanauts
Full load displacement	440,000 lbs	Nine view ports	6 in
On bottom weight	76,000 lbs	Two medical locks	14 in
Habitat volume	2,800 cu ft	Temperature control	inside heaters
Hatches			outside insulation
Main dive	36 x 42 in	Dehumidifiers	
Emergency	(2) 30 in diameter		Laboratory & living areas
Top	30 in diameter	Power	50 KW AC 3Ø via umbilical
Loading	48 in diameter		batteries 800 A-hr
Fresh water	4,000 gals	Three fully independent main chambers	
Tow speed	4 knots	Fire water deluge system	
Ascent and descent time	1-2 hours	All essential controls direct—	
Two emergency transfer		independent of power	
capsules	175 cu ft each		

Note: These data were obtained from several sources including Fahlman, G., 1970, Support Facilities and Operations Makai Range Mobile Habitat, *Progress into the Sea Trans.*, Marine Technology Society, Washington, D.C., pp. 237-252, and Lentz, R., 1970, Design and Construction of the Makai Range Mobile Habitat, *Progress into the Sea Trans.*, Marine Technology Society, Washington, D.C., pp. 95-107.

equipped with an infrared oven, a refrigerator, a freezer, and a sink. An overall schematic of Aegir is shown in Fig. 4-40.

The catamaran pontoon on which the complex was mounted served as a stable platform for the habitat and provided ample storage space for breathing gases, freshwater, emergency batteries, and other supplies. The twin hulls, which served also as the main ballast tanks, provided good towing characteristics even in rough seas. Each was a 9 × 70 foot (2.7 × 21.3 m) cylinder divided into five watertight compartments with an internal pressure capability of 15 psig. The three main ballast tanks had a flood valve at the bottom and a vent valve at the top, as well as a blow valve that could be operated manually from the deck of the pontoon. Breathing gases and air for blowing ballast tanks were stored in 54 (1500 scf) gas supply tubes, mounted athwartships at deck level. With all ballast tanks blown, the habitat had a draft of about 6 feet (1.8 m). With the main ballast tanks flooded, Aegir had a positive buoyancy of about 10 tons. Mounted fore and aft on deck were two variable 5.6 × 41 foot (1.7 × 12.5 m) ballast tanks, divided into two sections by bulkheads. All controls and gauges for the variable ballast tanks were operated by the aquanauts from inside the control compartment. Freshwater was stored in four 1000-gallon rubber bags mounted inside the main ballast tanks.

On the deck also were located emergency batteries that could provide

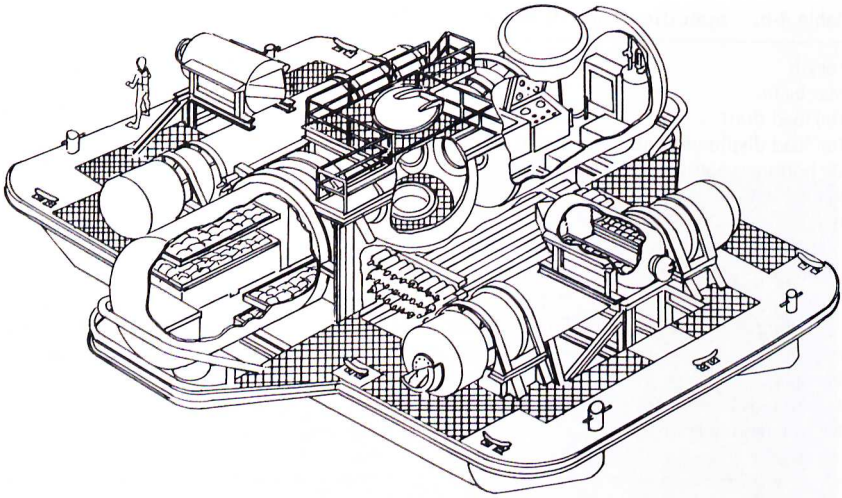

Figure 4-40. Aegir habitat schematic. (*Courtesy of Makai Range Inc., Honolulu, Hawaii.*)

power for 24 hours of operation, two emergency transfer chambers, and winches for controlling ascent and descent, as well as lifting loads up to 1.5 tons on and off the pontoon.

In addition to several test dives in 1969 to depths of 75 and 200 feet (22.9 and 61.0 m), Aegir was used for approximately twenty-five dives to 80 feet (24.4 m), three dives to 200 feet (60.1 m), and one dive to 516 feet (157.3 m) off Makapuu Point, Hawaii. These were open-sea dives in an area where heavy seas commonly prevail. The last dive to 200 feet (60.1 m) was performed under navy contract in December 1971 and was to have resulted in the final certification of the habitat by the Navy. A later dive to 520 feet (158.5 m) was planned but never executed due to lack of funds. The habitat, however, was certified to that depth by the navy.

Aegir also was used for numerous dry dives to depths of 400 to 500 feet (122 to 152.4 m) as part of programs carried out by the Physiology Department of the University of Hawaii and Webb Associates of Yellow Springs, Ohio. The final dry dive under this program was to 580 feet (176.8 m) in March 1975.

Few official records of Aegir's open-sea dives are available in printed form because of the dissolution of Makai Range, Inc. in February 1973. The record-breaking dive to 516 feet (157.3 m), however, has been described in some detail by Pegg (1971). The most significant medical aspect of this dive was the effect of the low habitat temperature on the six divers. The diving time, based on the estimates of the aquanauts, was less than

one-third of what could have been achieved had they been able to rewarm adequately in the habitat between dives. Because of their discomfort, morale deteriorated during the dive, although no request to abort was made. A significant performance decrement also occurred due to the usual problems associated with communication in a helium environment. Unfortunately, helium unscramblers were not used, and there were no diver-to-diver communication systems to aid while in the water. Although the aquanauts adapted eventually, the lack of communication aids required extensive writing to interact with the surface-support team and elaborate planning for each dive.

The aquanauts also experienced several ear infections. While such problems had been encountered in other habitat programs, they were perhaps more common in this Aegir mission because of failure of the shower to function properly and the high humidity. The cold habitat temperatures coupled with an inadequate diet resulted in a significant weight loss for some of the aquanauts. In spite of these problems, the dive was completed successfully and the final decompression achieved without any serious incidents.

Since 1975 the Aegir has been in the dock at the Makai Range facility with occasional preventive maintenance being performed. Although it may be used for further open-sea dives, a likely alternative is that the pressure chambers will be removed and relocated for use as dry experimental chambers.

LA CHALUPA, 1972-1975

La Chalupa was part of a program sponsored by the Marine Resources Development Foundation (MRDF) and the government of Puerto Rico. Program management as well as the design of the habitat were primarily the responsibility of the author (Koblick).

The habitat was designed to operate with a crew of five to depths of 100 feet (30.5 m) at distances of up to 10 miles (16.1 km) from shore. Program goals included increasing public awareness of Puerto Rico's marine facilities and activities, developing an undersea laboratory for use by scientists, training scientists in the use of an undersea laboratory and saturation diving techniques, training physicians in hyperbaric medicine, and extending the working depth of air and nitrogen-oxygen saturation diving.

The design of La Chalupa (a Spanish name for a Puerto Rican fishing boat which often capsizes) was based on an analysis of previous habitats, with emphasis placed on obtaining habitat mobility, minimizing the size of the support team, achieving a mission duration of 30 days for five aquanauts, and demonstrating the ability to handle the laboratory on the

surface in 5-foot (1.5 m) seas. It also was considered important to be able to decompress the aquanauts inside the habitat while on the seafloor, under tow, or at a shore base.

La Chalupa was designed as a barge-like structure containing two 8 × 20 foot (2.4 × 6 m) cylindrical chambers separated by a nonpressurized 10 × 20 foot (3 × 6 m) rectangular wet room (Fig. 4-41). Also included in the barge structure were a submergence control trim tank, two tanks for negative ballast once submerged, and 75 tons of concrete ballast (Fig. 4-42) Negative buoyancy, fully ballasted, was 22 tons.

One of La Chalupa's innovations was the hydraulic leg system designed to permit raising of the habitat out of the water for maintenance. The legs were sections of 24-inch (61 cm) steel pipe that could be retracted during towing, so the feet were flush with the barge bottom. At the dive site, the legs were lowered, holding the habitat 5 feet (1.5 m) off the bottom.

The control compartment contained equipment for environmental control, electrical services, communication, instrumentation, TV cameras, service appliances, and a 41-inch (104 cm) window (Fig. 4-43). Scientific equipment included a computer terminal and a real-time readout of local oceanographic data. The control compartment could withstand 50 psi

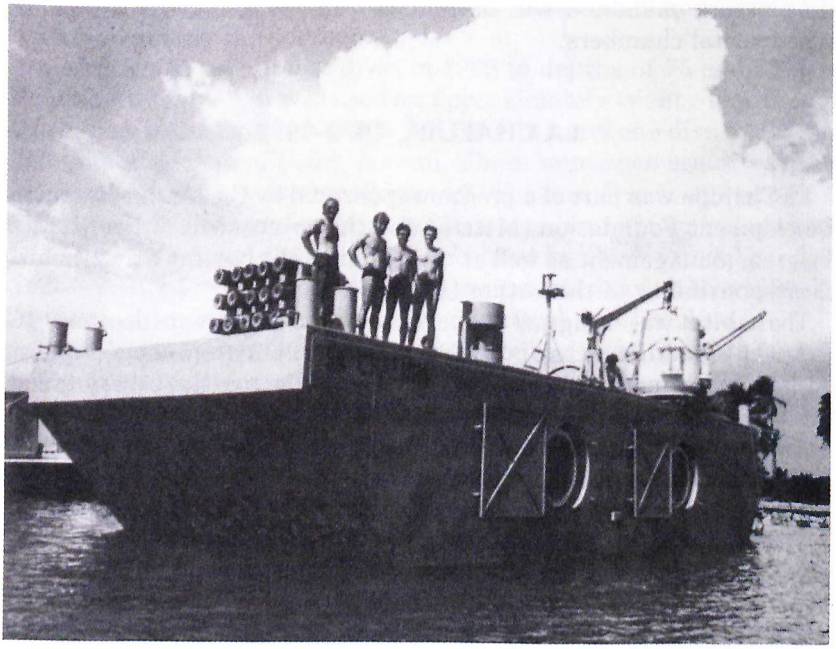

Figure 4-41. La Chalupa habitat at dock. (*Photo by Ian G. Koblick.*)

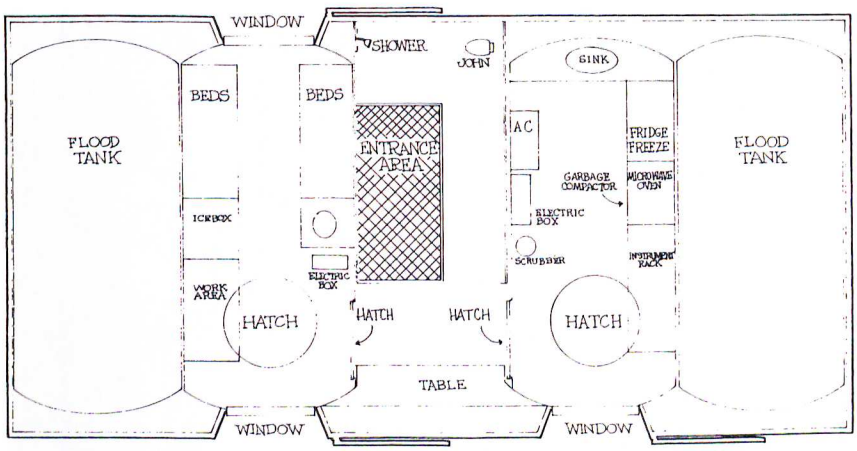

Figure 4-42. La Chalupa habitat schematic.

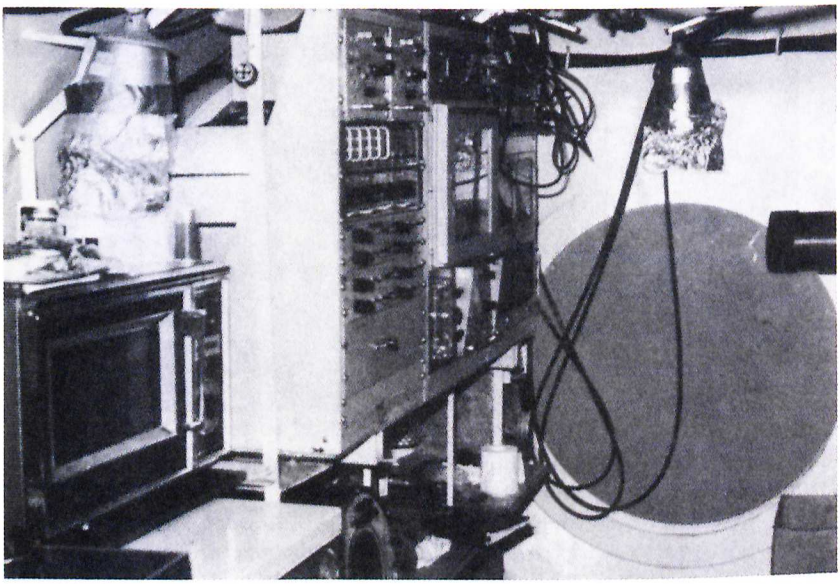

Figure 4-43. Control center of La Chalupa habitat. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

(3.5 kg cm^2) external pressure and in emergencies could be used as a decompression chamber on the seafloor.

The living compartment contained a TV camera, storage areas, four water beds, independent environmental controls, electrical service, communication and two 41-inch (104 cm) windows (Fig. 4-44).

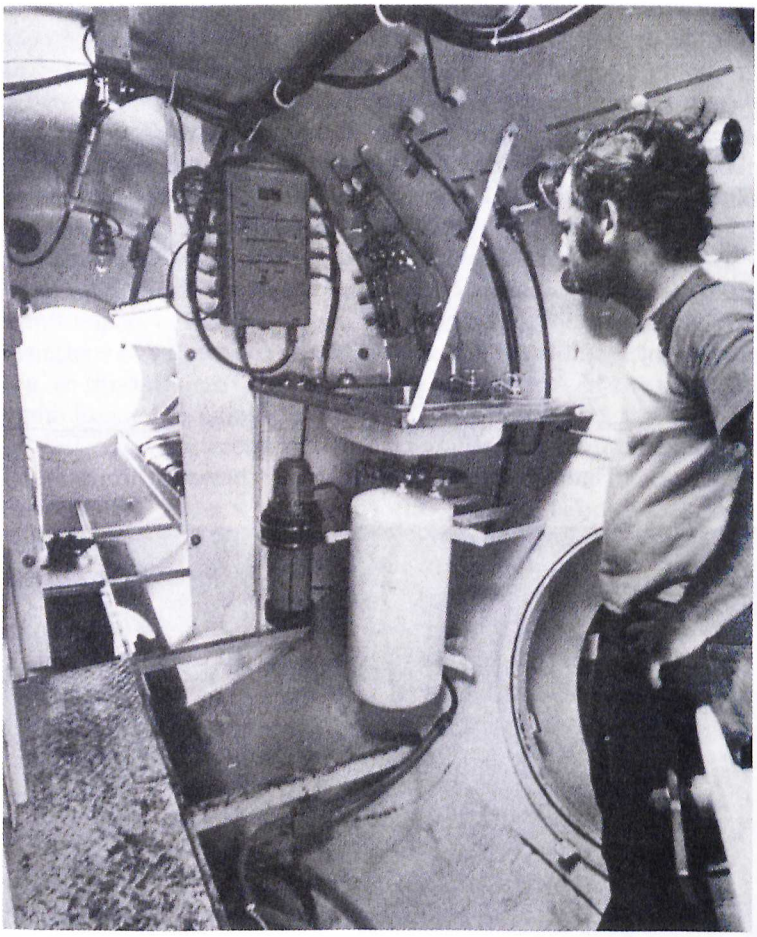

Figure 4-44. Living compartment of La Chalupa habitat. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

The wet room between the two cylinders provided a large, open utility area as well as serving as an entrance trunk for divers, a scuba filling station, and diving gear storage area (Fig. 4-45). The wet room also contained the toilet, a freshwater shower, and 35 feet^2 (3.2 m^2) of stainless steel table-top space for sorting specimens. An artist's conception of La Chalupa is shown in Figure 4-46.

La Chalupa's surface life-support system was housed in a modified 36-foot (11 m) fiberglass boat hull (Fig. 4-47). It contained generators,

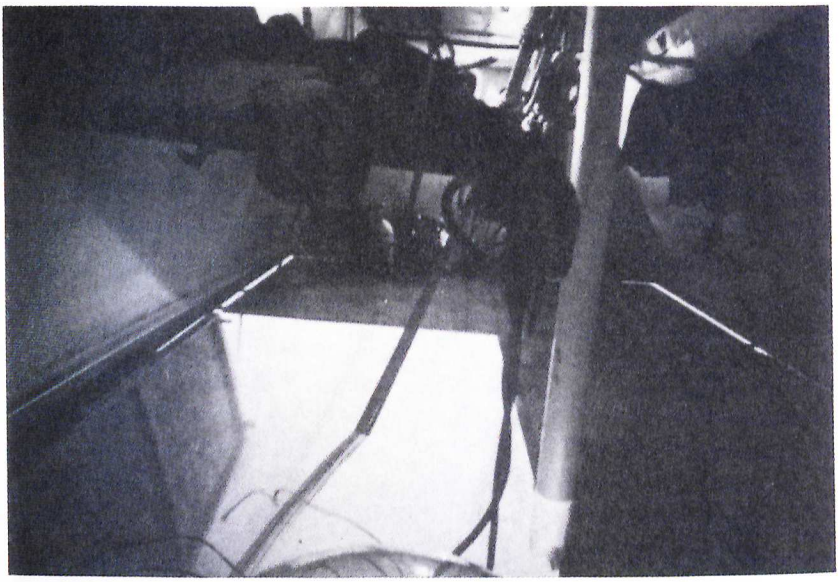

Figure 4-45. Diver entrance and wet room for La Chalupa habitat. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

compressors, air-conditioning, and communication systems. It also held a 1000-gallon (3785 l) water supply and an 800-gallon (3028 l) diesel fuel storage tank. The total diving system consisted of the habitat, the life-support buoy, and two safety boats (Fig. 4-48).

Stored on the barge were four 150-foot (45.7 m) hookah (air) hoses, oxygen and nitrogen cylinders, and 60 gallons (227 l) of emergency fresh water. In case of loss or failure of the life-support buoy, the habitat was equipped with emergency batteries to operate the CO_2 scrubbers and emergency lights for 48 hours. Additional independent emergency facilities included air, food, and CO_2 removal for as long as 10 days. As shown in Fig. 4-46, each chamber was equipped with an emergency escape pressurized PTC with mating flanges compatible with a shore-based decompression chamber that could be helicopter transported (Fig. 4-49). On shore was a van for diver support, and two 35-foot (10.7 m) travel trailers that provided mobile command, medical, and shore-based living facilities for support personnel.

The initial test dive lasted 3 days and took place in the port of West Palm Beach, Florida, where the habitat was built. The three aquanauts were Ian Koblick, project manager, Edward Geiger, an engineer with

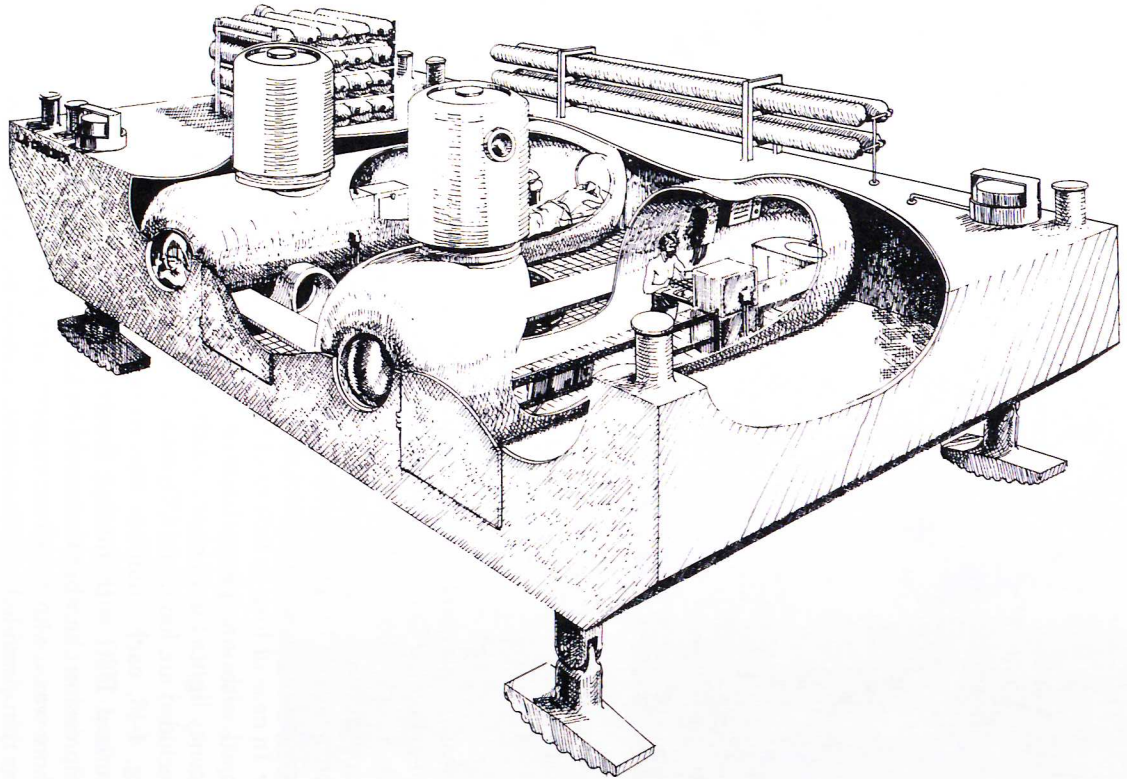

Figure 4-46. Artist's conception of La Chalupa habitat.

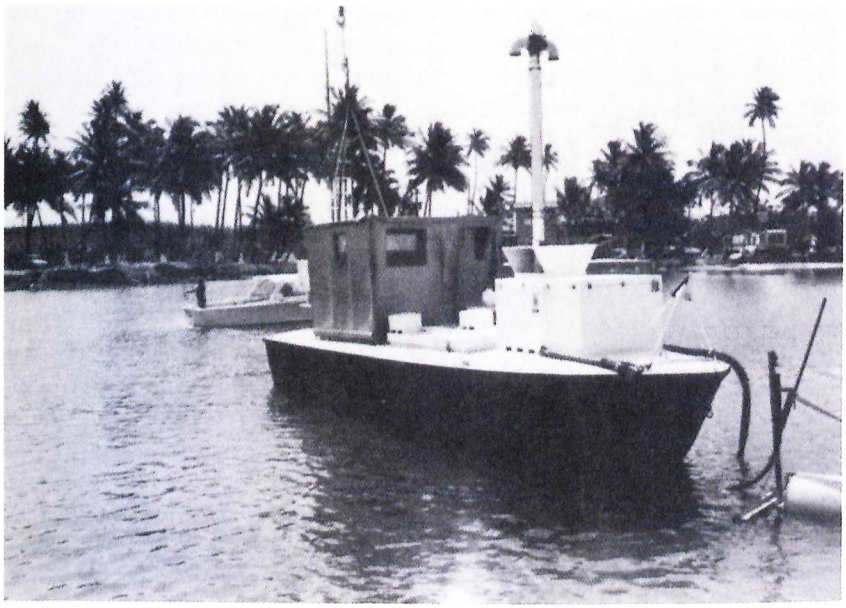

Figure 4-47. Life-support buoy for La Chalupa habitat. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)



Figure 4-48. La Chalupa habitat preparing to submerge. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

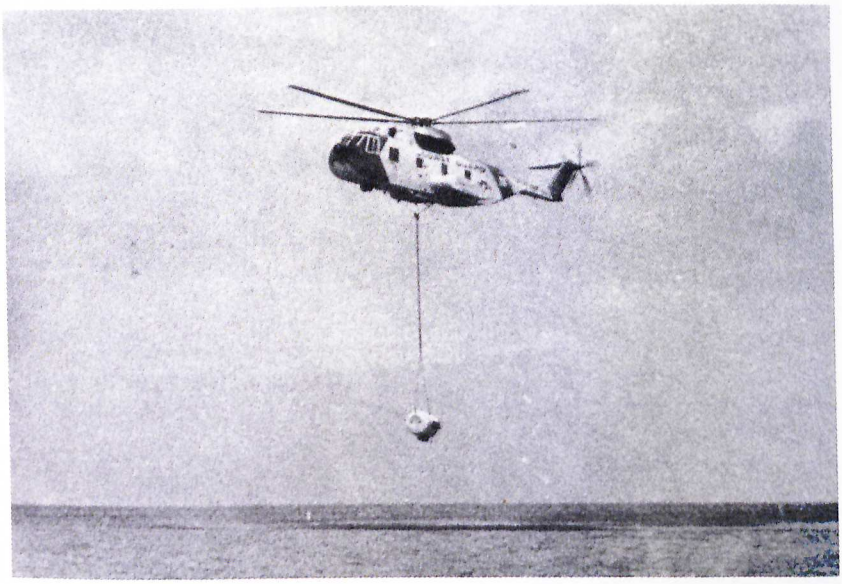

Figure 4-49. Simulated Coast Guard rescue operation of La Chalupa personnel transfer capsules. (*Courtesy Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

Perry Submarine Builders, and Russel Lloyd, a NASA engineer. They lived on the bottom at a depth of 28 feet (8.5 m) between October 14 and 17, 1972. Following this successful test dive, the habitat was floated aboard a ship furnished by the U.S. Navy and taken to Puerto Rico. One month later, the first open-sea scientific mission began 5 miles (8 km) off the southwest coast of Puerto Rico near Mayaguez, at a depth of 65 feet (19.8 m). Although some problems were experienced, the mission was concluded safely and confirmed the validity of the habitat design. During the following three years (1972 to 1974) eleven 2-week missions were conducted, during which over 50 scientists occupied La Chalupa in teams of four or five to study coral reef ecology, diving physiology, geology, and ocean engineering. Saturation depths ranged from 50 to 106 feet (15.2 to 32.3 m). The breathing mixture in the habitat was 8% oxygen and 92% nitrogen for the nine 50-foot (15.2 m) and 60-foot (18.3 m) missions and 5% oxygen and 95% nitrogen for the two 100-foot (30.5 m) missions. Excursions were made using air as a breathing gas either with scuba or hookah systems.

While the shallower missions were devoted to marine science and engineering, the two 100-foot (30.5 m) missions were designed to validate

vertical excursion diving profiles developed in the laboratory (Hamilton, et al., 1973). These 100-foot (30.5 m) missions were referred to as PRUNE I and II. The name reflected not only the condition of the diver's skin after the long excursions but also the acronym for Puerto Rico Undersea Nitrogen Excursion. Aquanauts for the first open-sea tests of these new procedures were Allan Waterfield, Seppo Kolehmainen, Michael Sheen, and ourselves.

The purpose of PRUNE I (April 24-May 4, 1973) was to test ascending excursion limits from the 100-foot (30.5 m) saturation depth. Once each day an ascending excursion was made by two or three divers. On each excursion the divers followed the habitat umbilical to the prescribed depth. All excursions were made breathing air either from a standard set of double cylinders or from an air hose attached to the habitat. During the excursions, which were made based on a saturation depth of 95 feet (29 m), the aquanauts constantly checked times and depths and questioned one another for signs or symptoms of bends. A brief summary of these excursions and their results are shown in Table 4-7. In general, no real bends were noticed during the 23 man-excursions, although a few niggles were observed by one aquanaut. Those responsible for this project be-

TABLE 4-7. Results of Ascending Excursions from a Saturation Depth of 95 fsw During PRUNE I

Excursion Depth (ft)	*(m)*	*Duration (min)*	*Habitat Mix, N_2/O_2*	*Equipment*	*Number of Divers*	*Symptoms*
60	18.3	55	96/4	Hookah	2	None
60	18.3	55	95/5	Hookah	2	Niggle, right knee[a]
50	15.2	30	90/10	Hookah	2	Niggle, left elbow
50	15.2	31	95/5	Scuba	3	None
40	12.2	18	94/6	Scuba	2	Slight niggle right knee
40	12.2	18	96/4	Scuba	2	None
30	9.1	7	94/6	Scuba	2	None
30	9.1	7	94/6	Scuba	3	Niggle, right knee
25	7.6	2	95/5	Scuba	3	Niggle left elbow
25	7.6	2	93/7	Scuba	2	None

Source: From J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, 1976, *Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures,* National Oceanic and Atmospheric Administration, Rockville, Md., p. 83.

[a]Same diver each time.

lieved that a 100-foot (30.5 m) storage depth was the optimal saturation level for nitrogen-oxygen breathing mixtures. Although no data exist, experts in the field of diving medicine think there would be a 3-minute margin of safety before the onset of the bends should a diver accidentally surface from this depth (Beckman and Smith, 1972). PRUNE I data convinced the authors that nitrogen narcosis was not a problem when divers are saturated at 100 feet (30.5 m) on a normoxic mixture of nitrogen and oxygen.

PRUNE II (March 18-29, 1974) tested the descending excursion tables developed in laboratory studies (Hamilton et al., 1973). Excursions were made from the 106-foot (32.3 m) saturation depth to depths up to 265 feet (80.8 m). These new procedures promised diving scientists additional latitude for exploring the top third of our U.S. continental shelf without requiring exotic breathing mixtures and equipment. During PRUNE II, 20 man-excursions were made to depths up to 265 feet (80.8 m) and for times up to 4 hours. The dives were complicated by the local topography, which required the aquanauts to ascend over a hump for each descending excursion (Fig. 4-50). This hump also prevented testing the excursion times to their fullest because of the short ascent on the way back to the habitat. Diving profiles for these excursions are shown in Table 4-8.

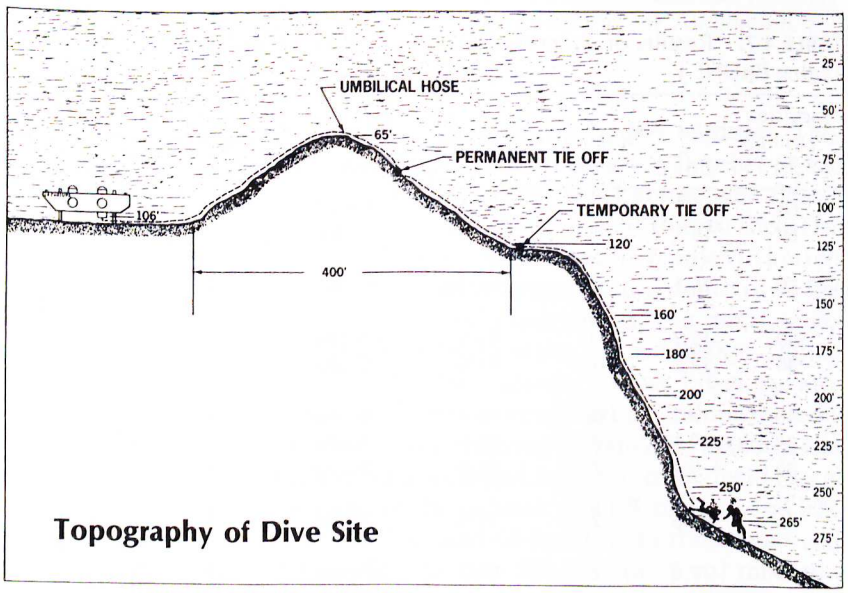

Figure 4-50. Bottom topography for PRUNE II descending excursion dives made during La Chalupa mission. (*Courtesy of National Oceanic and Atmospheric Administration.*)

Table 4-8. Descending Excursion Profiles from Saturation at 106 fsw during PRUNE II (Time in Minutes)

Excursion No.[a]	Maximum Depth Ft.	Maximum Depth m	Time to 120 ft (36.6)	Time at 120 ft (36.6)	Time to Maximum Depth	Time at Maximum Depth	Time to 120 ft (36.6)	Time at 120 ft (36.6)	Time to habitat
1	160	48.8	11	2	1	239	3	5	12
2	180	54.9	10	2	1	64	3	2	8
3	180	54.9	10	2	1	64	4	1	10
4	200	61.0	17	2	10	17	4	2	15
5	200	61.0	17	2	2	26	6	1	11
6	225	68.6	12	1	3	12	3	1	5
7	225	68.6	11	2	2	13	5	1	5
8	250	76.2	13	13	4	4	5	2	24
9	250	76.2	12	8	10	2	6	2	8
10	265	80.8	7	8	5	1[b]	13	4	8

Source: From J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, 1976, *Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures,* National Oceanic and Atmospheric Administration, Rockville, Md., p. 89.

[a]Two divers each excursion

[b]Aborted because of nitrogen narcosis in one diver. Both divers ascended to 200 ft and stayed for 8 min.

The La Chalupa program demonstrated the advantages of a mobile seafloor habitat system designed with the needs of scientists in mind. The conclusions based on the first nine missions of La Chalupa during which 42 scientists lived and worked on the seafloor, follow (Olsen, Koblick, and Sheen, 1974).

Forty-two scientists spent over 1600 hours in the water and made over 1700 dives varying in length from 5 minutes to 6 hours.

Most dive time spent during a mission (two weeks) by any one scientist was 69 hours.

Saturation diving permits short intervals between dives that are not possible when diving from the surface.

Habitat diving reduces risks associated with diving and boat operations at night (35% of the mission dives were made at night)

There appears to be a 4 or 5 day period of acclimatization at the beginning of a mission during which work output is low. This is followed by a repeated cycle of 4 days of high productivity and 1 day of reduced output.

To achieve the same daily in-water schedule when diving from the surface, over 8 hours of decompression would have been required each day.

Previous surface-based diving experience did not affect diver performance.

Experienced saturation divers tended to have greater cumulative dive time than inexperienced divers.

Inexperienced divers tended to have over 6 hours greater dive times if they were in missions with experienced saturation divers.

The final mission with the La Chalupa habitat was completed on June 6, 1974. The habitat remained in Puerto Rico at the operational site until the spring of 1976 when it was towed to Miami, Florida, and left unattended in a local shipyard. In early 1980, the habitat was purchased and refurbishment begun for commercial operations in the Caribbean.

As reflected in Table 4-9, the decade spanning 1965 through 1974 saw a significant expansion and sophistication of seafloor habitat programs. As saturation diving techniques and undersea technology improved, ocean engineers no longer were satisfied with constructing what essentially were survival shelters. Similarly, the pioneering aquanauts of the early 1960s whose primary function was to survive gave way to aquanaut scientists whose goals were to conduct scientific investigations. In the next chapter we delve deeper into the workings of habitats and compare the relative strengths and weaknesses of their design.

Table 4.9. Major Habitat Programs, 1965-1974

Date	*Sponsor*	*Project Name*	*Depth (ft)*	*Duration*	*Location*	*Dwelling Type (size in ft.)*	*Breathing Gas (%)*
Aug 1965	US Navy	Sealab II	205	15-30 days	La Jolla, California	12 × 57 cylinder	4.0 O_2 11.0 N_2 85.0 He
Sept 1965	J. Cousteau	Conshelf III	328	22 days	France Med. Sea	18 Sphere	2.5 O_2 97.5 He
Sept 1965	Marine Contracting Inc. and Westing-house Corp.	Smith Mountain Dam (Cachalot)	143-200	4 mo	Roanoke, Virginia	5 × 8 dry chamber	
Aug 1966	Gulf Oil Co.	Gulf Saturation Project (Cachalot)	240	4 mo	Gulf of Mexico	5 × 8 dry chamber	
1966 1983	Perry Submarine and NOAA	Hydrolab	50-60	1-14 days	Bahamas, Virgin Islands	8 × 16 cylinder	Air
1968 1974	USSR (Institute of Oceanology)	Chernomor	49-98	4-56 days	Black Sea	9.5 × 26 cylinder	10-13 O_2 87-90 N_2
1968 1972	Japan	Seatopia	98.4	2 days	Yokosuka, Japan	7.5 × 34.6 cylinder	7.2 O_2 14.2 N_2 78.6 He

(continued)



Table 4.9. *(continued)*

Date	*Sponsor*	*Project Name*	*Depth (ft)*	*Duration*	*Location*	*Dwelling Type (size in ft.)*	*Breathing Gas (%)*
1968 1976	Institute of Aviation Medicine, W. Germany, Biologic Institute, Helgoland, GKSS	Helgoland	328	7–14 days	Baltic Sea North Sea, West Atlantic, U.S.A.	19.7 × 29.5 cylinder	0.35 ATA O_2
1969 1970	US Navy Interior Dept. NASA, General Electric Co.	Tektite	42	14–60 days	U.S. Virgin Islands	12.5 × 18 vertical cylinders	8.0 O_2 92.0 N_2
1969 1975	Makai Range	Aegir	580		Hawaii	9 × 15 cylinders (2)	
1972 1974	Marine Resources Development Foundation	La Chalupa	50–106	3–14 days	Puerto Rico	8 × 20 cylinders (2)	8.0 O_2[a] 92.0 N_2 5.0 O_2[b] 95.0 N_2

[a] 50 feet
[b] 100 feet

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Chapter 5

Habitat Design and Operation

HABITAT SHAPE

Undersea habitats have come in many shapes, sizes, and even colors. The reasons for such variety can be attributed to pure aesthetics, nationality, operating locality, and in some cases, the availability of used parts from local junk yards and factories. Habitats have been built from cement mixers, boilers, rubber sheeting, molasses barrels, and railroad tank cars. Penzias and Goodman (1973) listed 41 habitats, of which 24 were cylinders, 3 spheres, and 14 of miscellaneous shapes and configurations. The shapes of habitats discussed in chapters 3 and 4 are depicted in Fig. 5-1.

Many factors determine the shape of a habitat. Will it have to withstand internal or external pressure or both? What will the maximum pressure be? Is the habitat to be a fixed seafloor structure or moved from site to site? In what sea states can it be expected to be deployed and operated? How far from a support base will it be used? Will it be towed to its site or handled by dockside or barge-mounted cranes? How many people will it house? Before beginning to design an undersea habitat, these and many more questions must be answered.

The most common shapes for undersea habitats and pressure vessels are the cylinder and the sphere. Although a cylindrical shape is more

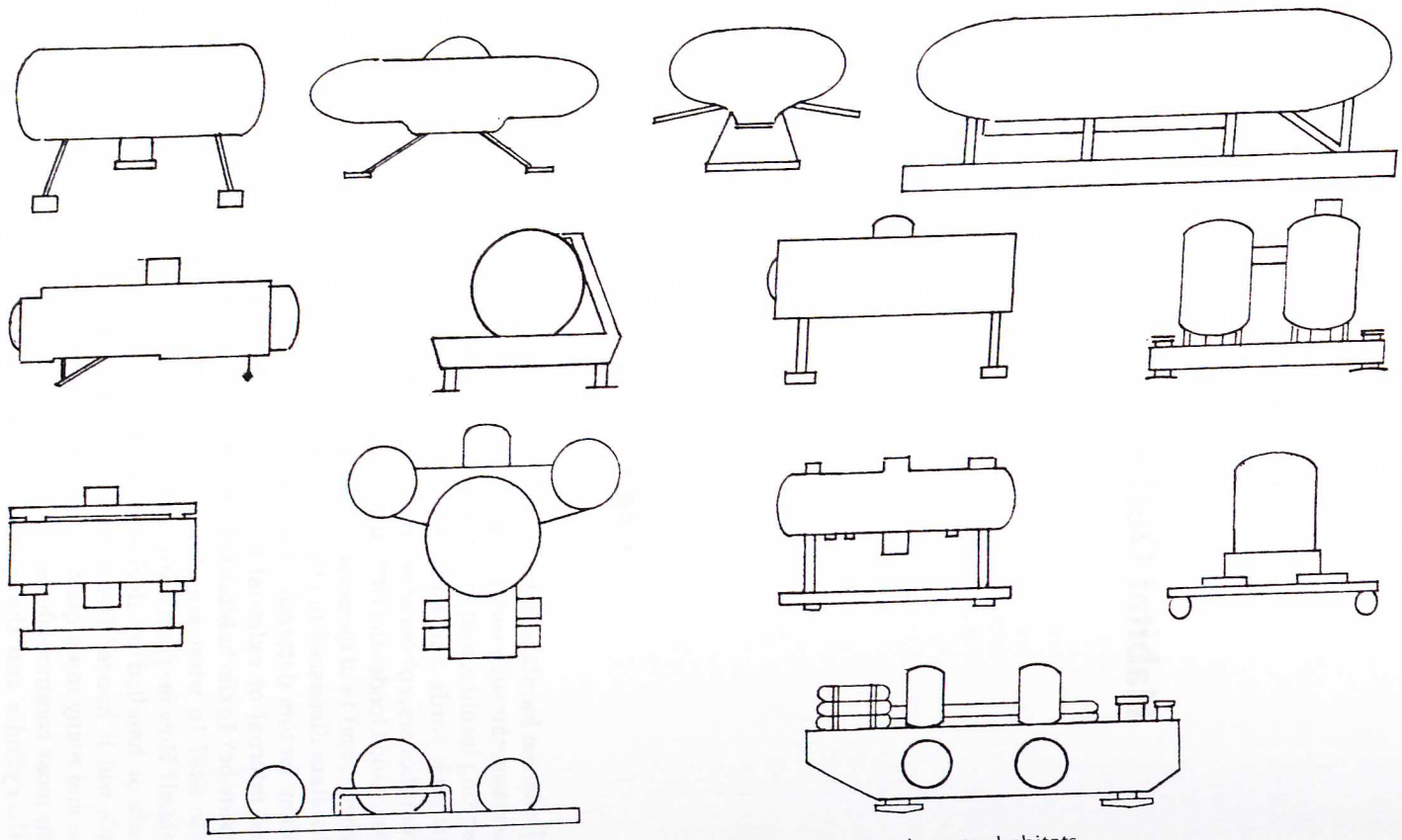


Figure 5-1. Representative shapes and configurations of underwater habitats.

functional, Penzias and Goodman (1973) have pointed out that a sphere has a number of unique features:

To package a given volume, a sphere requires the minimum shell area.
To contain this volume against a given pressure—internal or external—a sphere requires the least shell thickness.
It follows from the preceding two properties that a sphere requires a minimum volume of shell material and is thus the lightest possible pressure vessel shape in the amount of weight.
Any elastic envelope pressurized internally will attempt to assume a spherical shape and will come progressively closer to this shape as internal pressure is raised.

Although the same basic engineering principles apply to the construction of a pressure vessel being designed for external pressure as for internal pressure, there are two differences to keep in mind. Penzias and Goodman (1973, p.429) describe them as follows: For externally pressurized spheres,

> the basic membrane stress, remote from the collapse pressure, is one of compression. The applied load attempts to compact the vessel and push seams together. The failure mode, on thin walled vessels, is one of instability, in that initial deformations caused by the load lead to a shape which worsens the stress condition. In contradistinction, vessels under internal pressure try to bulge out, smooth corners and ease the stress conditions.

Readers interested in the design and construction of pressure vessels should refer to engineering sources on the subject such as Myers, Holm, and McAllister (1969), Penzias and Goodman (1973), and Busby (1976).

While most of the habitats described in Chapters 3 and 4 were pressure vessels constructed or adapted for use as a habitat, many of the smaller habitats described later in Chapter 9 not only varied in shape but were not designed or used as pressure vessels at all. In these cases, the habitat was a simple enclosure in which air pressure inside kept the water out. Essentially no pressure differential existed between the surrounding water and the habitat interior. This works fine as long as internal pressure can be adjusted to compensate for any variations in external pressure and there is no intention of using the habitat as a decompression chamber. But some habitats were used for decompression anyway, even though they were not pressure vessels, by physically raising them through the water column and stopping at prescribed depths, much as a scuba diver makes in-water decompression stops on the way to the surface.

MATERIALS FOR HABITAT HULLS AND PRESSURE VESSELS

Materials selected for habitats, as for any other marine use, should have intrinsic resistance to the corrosive effects of seawater or a means to protect them effectively. In addition, materials subjected to repeated stress cycles, such as pressure vessels, must be able to withstand such cycles without fatigue failure. Additional parameters that must be considered when designing a habitat include purpose, size, configuration, operational depth, air and water temperatures, hatch and port requirements, manufacturing, testing, and maintenance techniques, and transportation to the operational site.

High-strength metals, glass, and ceramics have characteristics that make them particularly appropriate for use in underwater structures. Table 5-1 lists some of the materials used for pressure vessels and the parameters guiding their selection. Figures 5-2 and 5-3 present a qualitative comparison of factors influencing the selection of materials for underwater use.

To date, all habitats incorporating a pressure vessel have been constructed of steel, titanium, or aluminum. Each material has advantages and disadvantages with respect to such factors as corrosion resistance, fatigue, fracture resistance, ductility, and yield strength. The advice of experts should be sought when designing for marine applications, especially those involving pressure vessels. Elastic properties of some steels are severely affected by exposure to low temperatures such as those found in northern waters and must be chosen carefully. Although habitats operating in cold waters generally are heated, they should be designed to operate in 28°F (−2.2°C) temperatures. Judicious selection of materials will avoid many of the difficulties experienced in the past.

The use of concrete for submerged hulls probably will increase in the future because of the material's advantages of low cost and ease of fabrication (University of New Hampshire, 1972). Concrete has excellent strength qualities under hydrostatic pressure loads and excellent durability in seawater, and it may be used readily for the construction of complex shapes. With concrete, wall thickness of large habitats can be increased as necessary to achieve a neutrally buoyant structure, eliminating the need for additional ballast materials or massive anchoring systems. Permeability of seawater in concrete is not a problem, and hull strength is maintained both with and without various penetrations. The use of polymer-impregnated concrete results in an even a more impermeable, stronger material.

Another approach is the use of a synthetic fabric, inflatable hull. This

Table 5-1. Materials for Deep Submergence Structures

Parameter	*HY-80*	*HY-100*	*HY-130/ 150*	*Steel 12Ni-5Cr -3 Mo Maraging*	*HP-9-4-20*	*18Ni-8C0 2.6 Mo Maraging*	*Titanium 6A1-4V ELI*	*6A1-2Co -1Ta-0.8Mo*	*Aluminum 7079-T6*	*Glass Borosilicate Corning Code 7740*
Density (lb./in.^{3})	0.28	0.28	0.28	0.286	0.28	0.293	0.16	0.16	0.10	0.0806
Elastic modulus (psi. $\times 10^{-6}$)	30	30	29	27.5	29	27.5	15.8	17.0	10.4	9.1
Compressive yield strength (psi. $\times 10^{-3}$)	80	100	150	180	180	180	120	108	60	Greater than 300
Yield Strength Density (in. $\times 10^{-3}$)	286	357	535	630	643	614	750	675	600	3720
Linear thermal expansion Coefficient (in./in. $\times$ °F $\times 10^6$)	7.1	7.1	7.3	6.3	6.4	5.9	4.9	5.0	13.1	1.83
Temperature range (°F)	80-880°	80-880°	80-1100°	80-800°	68-800°	80-800°	32-212°	32—1200°	68-212°	32-572°
Fracture toughness	Very good	Very good	Very good	Good	Good	Fair	Fair	Good	Poor	Poor

(continued)

Table 5-1. *(continued)*

Parameter	Steel					18Ni-8C0 2.6 Mo Maraging	Titanium		Aluminum 7079-T6	Glass Borosilicate Corning Code 7740
	HY-80	HY-100	HY-130/ 150	12Ni-5Cr -3 Mo Maraging	HP-9-4-20		6A1-4V ELI	6A1-2Co -1Ta-0.8Mo		
Low cycle fatigue resistance	Good	Good	Good	Fair	Fair	Fair	Good	Good	Fair	Good
Creep resistance at sea temperatures	Good	Good	Good	Good	Good	Good	Question-able	Question-able	Good	Good
General corrosion resistance	Poor	Poor	Poor	Poor	Poor	Poor	Excellent	Excellent	Poor	Excellent
Stress-corrosion resistance in structures	Excellent	Excellent	Excellent	Fair	Good	Fair	Good	Very Good	—	Excellent
Weldability (heavy sections)	Excellent	Excellent	Good	Good	Good	Good	Question-able	Question-able	Not weldable	Can be welded or cemented
Availability (heavy sections)	Excellent	Fair	Fair	Fair	Poor	Fair	Fair	Poor	Fair	Fair
Plate Cost[a]	Low	Low	Low	Medium	Medium	Medium	High	High	Medium	Medium[b]

[a] Cost ranges: low—$1/lb. or less; medium $1 to $3/lb.; high—$3/lb. or more.

[b] Cost of untreated hemisphere blanks, $2.50 $7.50/lb.

Source: From Penzias, W. and M. Goodman, 1973, *Man Beneath the Sea—A Review of Underwater Ocean Engineering*, John Wiley and Sons, New York, p. 451.

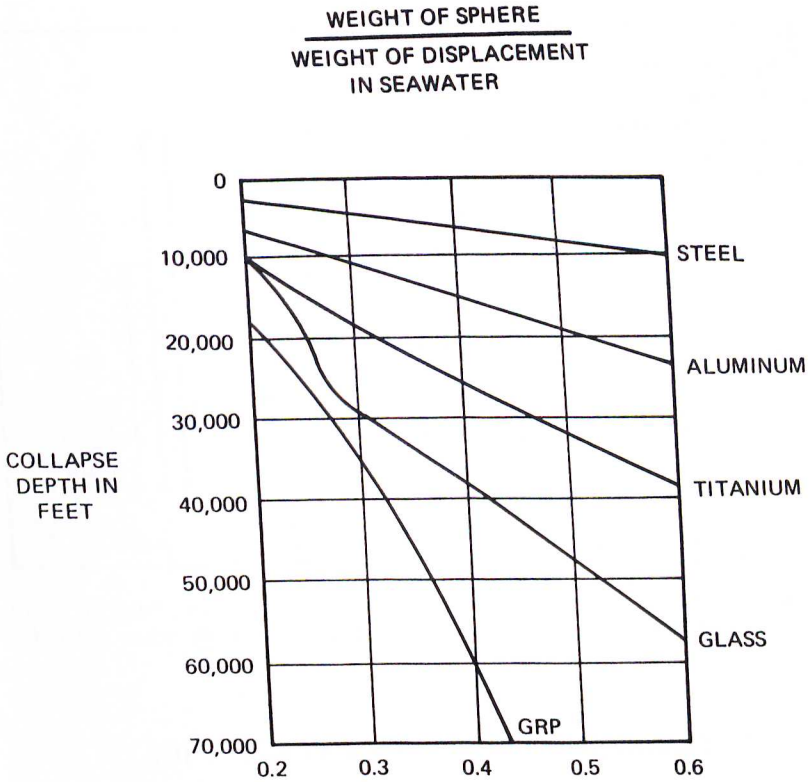


Figure 5-2. Weight/displacement ratio vs. collapse depth of five material candidates for spherical pressure hulls. (*From R. Busby, 1976, Manned Submersibles, Office of the Oceanographer of the Navy, Alexandria, Va., p. 248.*)

technique, used by Link in his early Man-in-the-Sea programs and by the Russians in their SPRUT program, achieves its strength by maintaining an internal pressure slightly greater than the ambient water pressure. Habitats constructed of this material were small and/or temporary, and therefore for short-duration missions.

In general, the state of the art for materials suitable for construction of undersea habitats is well known. Information relating to the development, fabrication, documentation, certification, and operation of undersea systems can be obtained from the American Society of Mechanical Engineers, the American Bureau of Shipping, or from such excellent texts as Myers, Holm, and McAllister (1969) and Busby (1976).

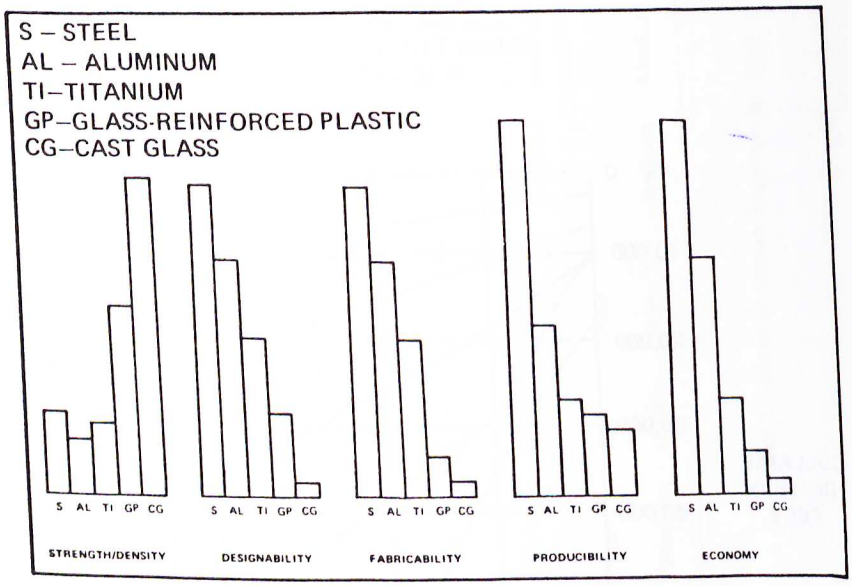


Figure 5-3. Qualitative comparison of pressure hull materials. (*From R. Busby 1976, Manned Submersibles, Office of the Oceanographer of the Navy, Alexandria Va., p. 248.*)

CORROSION AND PROTECTIVE COATINGS

Corrosive action of seawater on metals is a long-standing problem Even properly selected metals are subject to attack by sessile organisms that can quickly rupture protective coatings. The basic process of corrosion involves an electrochemical reaction between the environment and metallic surfaces. The four basic elements of corrosion according Penzias and Goodman (1973, p.447) are:

The anode area, where corrosion takes place, and current, in the form metal ions, enters the electrolyte.
The electrolyte containing ions that carry current to the cathode, in case usually seawater.
The cathode area at which reduction takes place and current enters f the electrolyte.
A current path within the metal component which completes the curr

The electrochemical process of corrosion can be placed into four ge categories: general corrosion in which the corrosive action is distrib uniformly over the surface of the metal; galvanic corrosion where dissimilar metals form an electrochemical cell; crevice corrosion, w

occurs when seawater is admitted to a narrow, isolated area; and stress corrosion where crack propagation is observed on certain alloys when small surface flaws are subjected to tensile stresses in the presence of seawater.

Since habitats remain submerged in salt water for long periods of time, it is essential that careful thought be given to the prevention of corrosion through the use of protective procedures and coatings. Galvanic corrosion can be minimized by avoiding contact between metals that generate a high potential. The galvanic effect, however, can be used as a protective device itself. Several techniques have been used. One, referred to as anodic protection, involves the use of a sacrificial metal placed on the hull or some other strategic part to be protected. As the electrochemical reaction takes place, this metal is attacked preferentially, leaving the protected portion of the habitat undisturbed. The most common practice is to use a zinc anode as the sacrificial metal. These anodes should be located so they can be replaced periodically when the habitat is undergoing maintenance. If the habitat is to remain on the bottom for extended periods, the anodes should be installed so they can be changed under water.

A second anticorrosion technique is cathodic protection. This method uses an electrical current from external sources to create a current equal to the electrochemical current produced by the system being protected. In order to monitor the effectiveness of a cathodic protection system, annual inspections are recommended (Busby, 1978). Inspection can be carried out by a diver with a hand-carried instrument. A reading usually can be obtained in about 1 minute.

The proper use of protective coatings can greatly reduce corrosive action of seawater. A properly selected paint system not only will protect metal surfaces but will reduce annual maintenance costs of sandblasting, chipping, and repainting. A good coat of paint can last 5 to 10 years if maintained properly. A number of different types of nonmetallic coatings are now available, including oil-base paints, epoxies, and inorganic zinc. New coatings on the market combine corrosion protection with inhibitors against marine fouling.

Care must be taken to select nontoxic protective coatings for interior surfaces of chambers where human occupancy is anticipated. Even when nontoxic paints are used, at least 30 days should elapse between completion of painting and the beginning of a mission where aquanauts will be living in a closed environmental system. An example of the successful use of expoxy paint is the La Chalupa habitat. The paint was found to be in excellent condition 8 years after it was applied. All it required was a careful washing. When applying the final coat of paint, extreme care must be taken to prevent small particles such as sand from remaining in

crevices or sticking to welds. Such particles will prevent paint from adhering and may ultimately serve as the source of crevice corrosion.

HULL PENETRATORS

An electrical penetrator passes power or electrical signals through the wall of a pressure hull or battery pod. It must seal and insulate the through-hull conductors and preserve the hull's watertight integrity under both normal and abnormal (short-circuit) conditions. Because many companies in the United States manufacture electrical penetrators and connectors, variation in design and components precludes a single

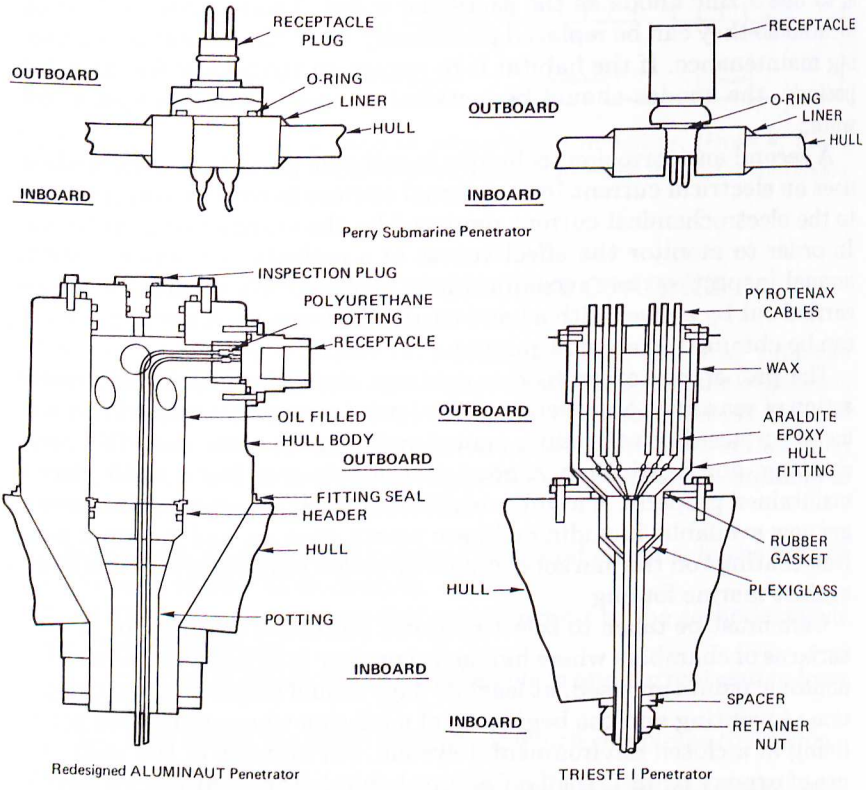


Figure 5-4. Some examples of submersible electrical penetrators. (*From R. Busby, 1976, Manned Submersibles, Office of the Oceanographer of the Navy, Alexandria, Va., p. 340.*)

schematic representation. An excellent source for information on hull penetrators is the U.S. Naval Ship Engineering Center report (1971).

Four basic design factors should be considered when selecting hull penetrators: entry configuration, hull fastening methods, hull sealing methods, and hull insert types (Busby, 1976). With the penetrator entry, the cable can enter the hull vertically or at any angle from vertical to horizontal, although horizontal entry is the most advantageous because the cables can be supported and protected more easily. Three examples of electrical penetrators are illustrated in Figure 5-4. Hull fastening methods are illustrated in Figure 5-5 and can be summarized as follows:

Bolted flange: Bolting directly to the hull may produce a stress concentration area wherein the flange consumes a large surface area outside the hull and also may cause crevice and other corrosion problems.

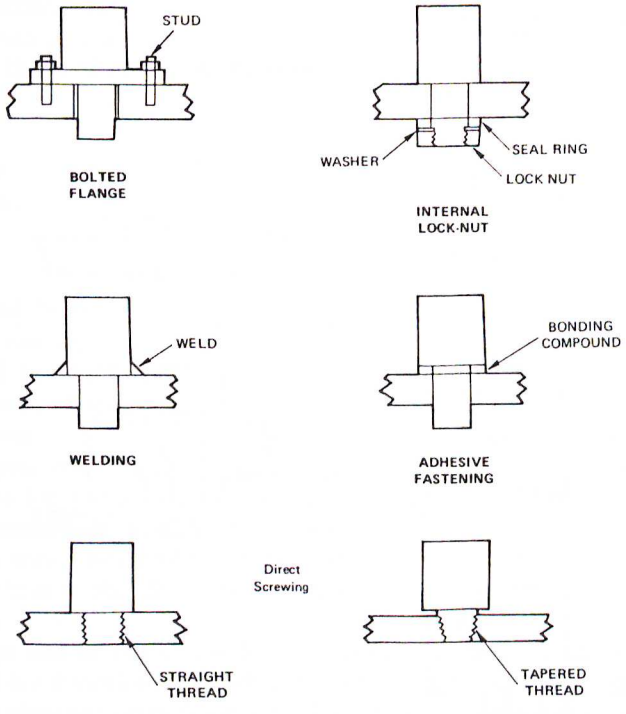


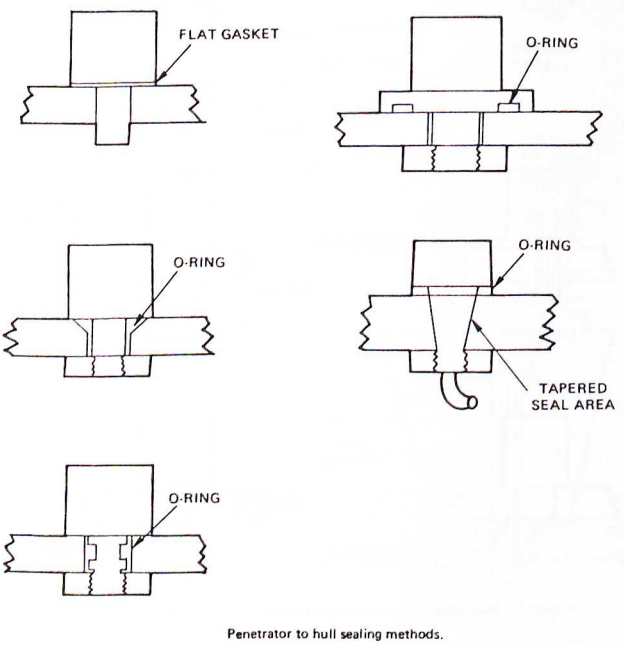
Figure 5-5. Penetrators, fastening, sealing, and insert methods. (*From R. Busby, 1976, Manned Submersibles, Office of the Oceanographer of the Navy, Alexandria, Va., p. 344.*)

Internal lock nut: The most widely used method; causes the least problems.
Welding: Conserves space but is permanent and therefore hampers replacement for maintenance; some hull materials are not weldable.
Adhesives: Have a low confidence level at present.
Direct screwing: Poses machining and stress concentration problems.

Because replacement or removal of the penetrator for inspection is a general requirement, the use of welding or adhesives is precluded.

Figure 5-6 shows the use of a flat gasket, which requires periodic repressurization, and O-rings, which provide excellent low-pressure seals and are most widely used. Also shown is a metal-to-metal tapered seal for use when a metal-to-metal contact is desired. Several basic hull insert penetrators are shown in Figure 5-7. Threaded, tapered, and conical inserts are found in most submersibles. In the conical insert, a plastic gasket is pressurized into the cone area by tightening an inboard locknut. Stepped-hole inserts create stress concentrations, and thus a tapered hole is favored, although individual matching of each penetrator may be required to fit each insert. The hull insert material must be the same as the hull material, and full penetration welds at the insert-hull interface





Penetrator to hull sealing methods.

Figure 5-6. Penetrator to hull sealing methods. (*From R. Busby, 1976, Manned Submersibles, Office of the Oceanographer of the Navy, Alexandria, Va., p. 344.*)

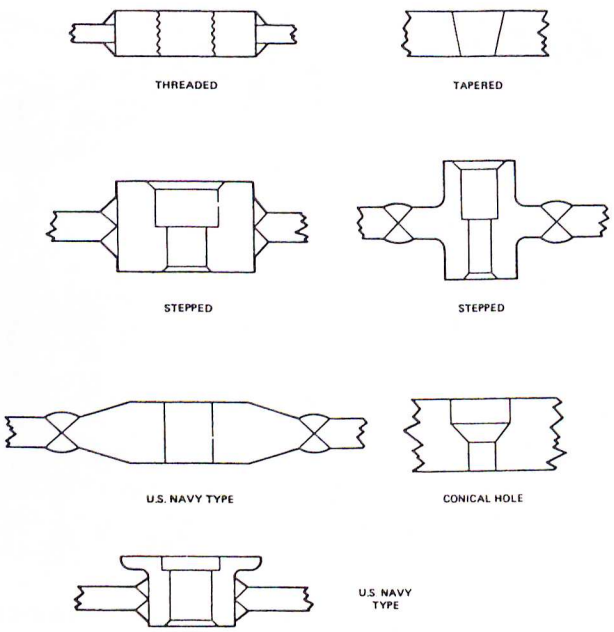


Figure 5-7. Typical hull inserts for electrical penetrators. (*From R. Busby, 1976, Manned Submersibles, Office of the Oceanographer of the Navy, Alexandria, Va., p. 345.*)

are desired. For depths down to 300 feet (91.5 m), electrical cables used for habitats can be carried through the pressure hull using stuffing tubes designed to meet military specifications. These are standard navy penetrators, which are usually used on board ships and were used in early submarines.

Hull penetrations for all gas lines, water lines, and sanitary drains should be located as low on the hull as possible to minimize flooding or loss of pressure in case a line is broken. Hull penetrations for plumbing of gas and water normally are medium-pressure or high-pressure piping screwed into a stainless steel coupling that has been welded through the hull.

Design and layout of the habitat should be such that penetrators are grouped by function. In addition, they should be separated from each other to eliminate interference with electronic equipment such as radios or computers. Electrical lines should be separated from water lines that could leak and cause shorts and corrosion. Electrical connectors should be located high in the habitat to protect them should the habitat partially flood and to facilitate repair from inside (Fig. 5-8).

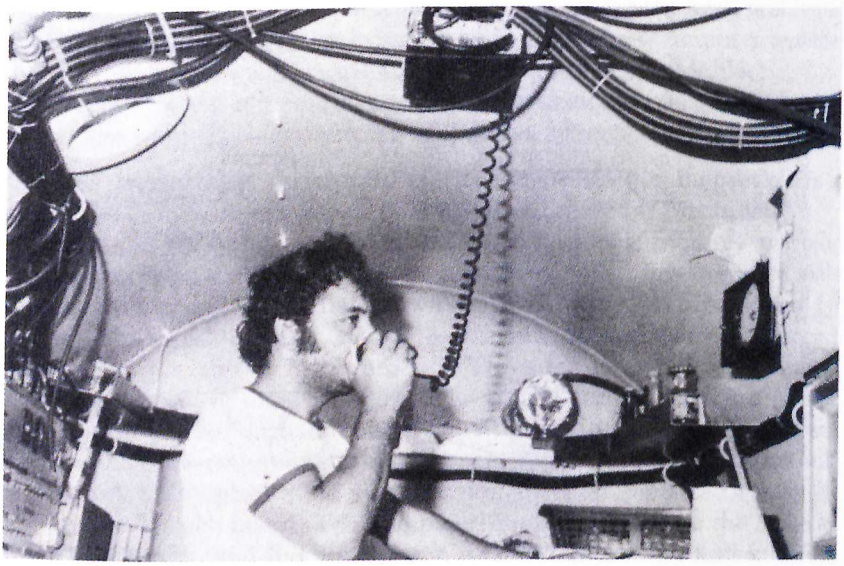


Figure 5-8. Ceiling-mounted communication and electrical system in La Chalupa. (*Courtesy of Marine Resources Development Foundation.*)

Simplicity and ease of maintenance should be the rule when selecting or designing hull penetrators. An analysis of failure modes reveals that most problems attributed to penetrators fall into one of four categories (Penzias and Goodman, 1973, p. 481):

Mechanical damage such as bent pins, stripped threads, and gashed or abraded cable jackets.
Loss of signal due to an open circuit, leakage, or interference.
A pressure leak admitting sea water to places where it should not be.
Short circuit and subsequent damage or destruction of an area by heat.

While failures are due to numerous factors and errors both operationally and during manufacture, many problems can be overcome by judicious planning. For example, using a hull feedthrough instead of connectors will eliminate failure modes associated with pins, coupling rings, and internal connector leaks.

In summary, experience has shown that a hull penetration system is most reliable when it is simple and is an integral part of the habitat. Whereas gas and water penetration should be low in the habitat, electrical penetrators should be high. Whenever possible, penetrators should be grouped by function, and neoprene or polyurethane jacketed wiring should be used.

PORTS AND WINDOWS

While engineers may feel that ports and windows in a pressure vessel present unnecessary design problems with respect to hull integrity, to live in the sea and not be able to observe the neighborhood and its residents is unacceptable to most aquanauts. Fortunately, almost all habitats constructed to date have contained ports that have served to enhance safety, permit scientific observations, relieve psychological tensions, and increase the joy of living in the sea.

These windows in the sea have come in many shapes and sizes, ranging from 4-inch (10.2 cm) peepholes to 42-inch (106.7 cm) picture windows. Ports have been designed in configurations that are flat, conical, hemispherical, or combinations of these. Depending on the nature of the habitat, ports have been designed to withstand internal or external pressure differentials or, in selected cases, to take pressure from both sides. While some were made of glass, most have been constructed of acrylic plastic (Plexiglas). Another plastic material that looks promising for future shallow-water habitats is polycarbonate. Its primary advantage lies in its superior resistance to impact.

The number, placement, and size of ports depends on the nature of the habitat, its primary function, and the availability of the required materials. Although the small, flat ports used in most habitats are comforting from a psychological standpoint, they offer very restricted viewing. Several habitats have incorporated large ports. Starfish House used by Cousteau for Conshelf II had large windows bolted to the chamber (Fig. 3-6). Because Starfish House was maintained at approximately ambient sea pressure, there was little differential pressure between the inside and outside of the port. The ports maintained their seal primarily because of the slightly overpressured interior of the habitat. Sealab II used 11 flat ports, 24 inches (61 cm) in diameter, designed to withstand an internal pressure of 125 psi. (8.8 kg/cm^2) (Fig. 5-9). Although these were fairly large, most were inconveniently placed behind equipment, on the back of counters, or other poor locations. The Tektite habitat contained six 24-inch (61 cm) diameter, ½-inch (1.27 cm) thick, acrylic hemispherical ports that provided a viewing angle of nearly 180 degrees (Fig. 5-10). Hemispherical ports, while excellent for viewing objects close to the habitat, introduce distortion at the sides and because they protrude from the exterior of the habitat and are susceptible to being smashed or having things drop on them from the surface. To minimize the chance of these problems, port covers were installed during transportation and emplacement of Tektite (Fig. 5-11).

The largest ports used for undersea habitats were those of Hydrolab (Fig. 5-12) and La Chalupa (Fig. 4-41). In both instances, the acrylic

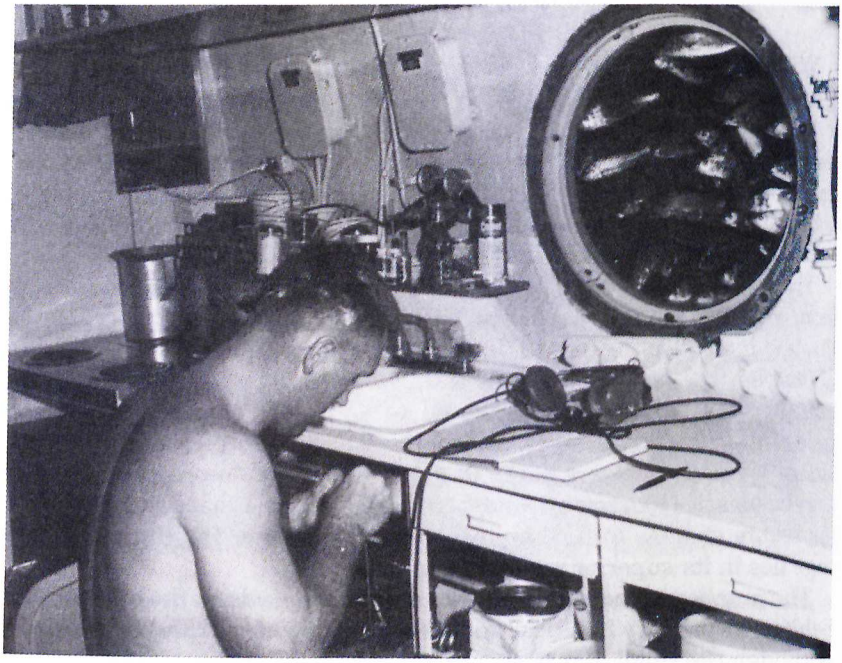


Figure 5-9. Interior of Sealab II showing 24-inch port. (*Official U.S. Navy photograph.*)

plastic ports were flat, 42 inches (106.7 cm) in diameter, and 4 inches (10.2 cm) thick. Hinged port covers were used on La Chalupa for protection (Fig. 4-41). Hydrolab had one port in the end of the single compartment, and La Chalupa had three ports—one in the equipment room and two in the living compartment. Because decompression was carried out inside both habitats, the ports were designed to withstand internal and external pressures up to 50 psi (3.5 kg/cm^2) for Hydrolab and 75 psi (5.3 kg/cm^2) for La Chalupa. The ports used for Chernomor and Helgoland (Figs. 5-13 and 4-36, respectively) also were flat but were considerably smaller than those of Hydrolab and La Chalupa.

Location of ports is critical. They should be placed so that breakage or leaks will not flood the entire habitat. This requirement precludes placing ports in the extreme upper parts of the habitat or on the overhead. This principle was compromised in the Tektite habitat when it was decided to place a cupola made of eight flat Plexiglas windows on top of one of the two chambers (Fig. 5-11). Its purpose was to permit an observer inside

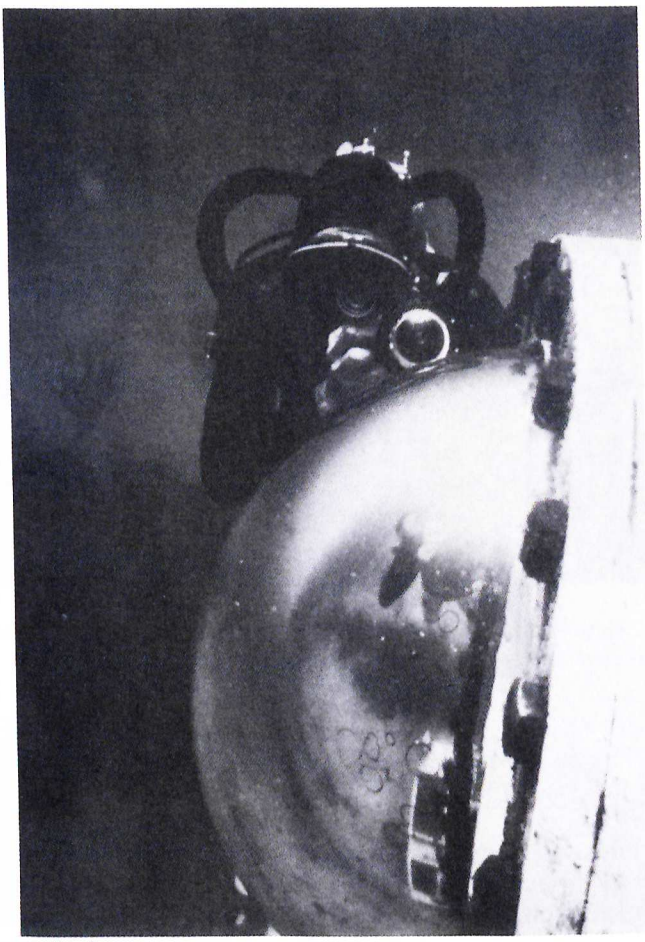


Figure 5-10. Tektite habitat 24-inch port. (*Courtesy of General Electric Company.*)

the habitat to have a full view of the surrounding area. Should any of the cupola windows have broken, flooding would have occurred in seconds because Tektite's two-level configuration resulted in a pressure differential of about 7.5 psi (0.53 kg/cm^2) between the cupola and the entrance hatch. No such incident occurred in either Tektite program. Figure 5-14 presents a summary of designs for ports that have been used in undersea habitats. An excellent and comprehensive source of information on acrylic ports is Stachiw (1982).

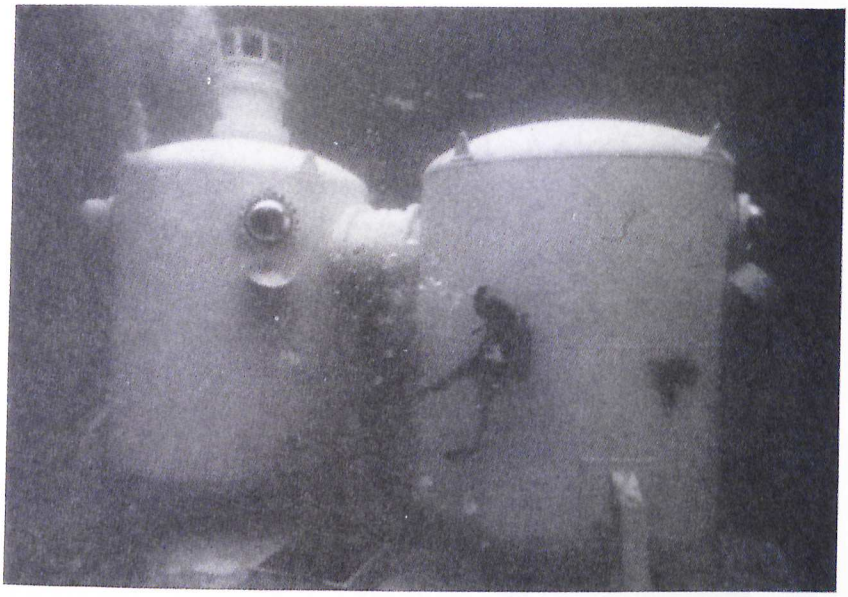


Figure 5-11. Tektite habitat showing protective port covers hanging below ports. (*Courtesy of General Electric Company.*)

HATCHES

Hatches are necessary with respect to maintaining the integrity of a pressure vessel. Whereas ports are made to look through, hatches are made to go through. When selecting a hatch, the first consideration usually is size. Generally it is desirable to keep the hatch as small as operational requirements will permit. Large hatches present handling problems because of weight and fabrication problems because of the increased reinforcement needed around the hatch opening. Although small hatches are desirable from an engineering viewpoint, experience has shown that most habitats were built with hatches so small they interfered significantly with daily operations.

Most hatch openings in habitats are circular or oval. They have ranged from the 32-inch (81.3 cm) entrance trunk on Hydrolab to the 48-inch (122 cm) hatch on Tektite. Hatches usually are round; this shape simplifies machining, and on spherical pressure vessels symmetrical distortion facilitates obtaining a good seal. For pressures usually encountered in habitats, slightly convex hatch covers with an O-ring seal are adequate.

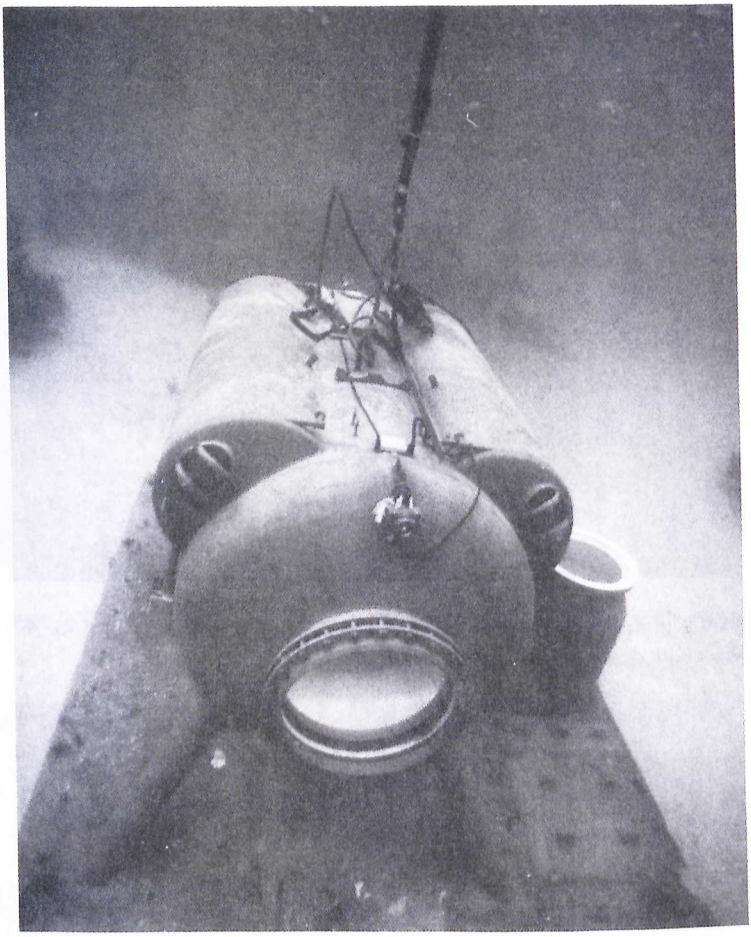


Figure 5-12. Hydrolab Habitat showing 42-inch port. (*Courtesy of Dick Clarke.*)

When the pressure vessel is subjected to internal pressure, the hatch is located inside the vessel and will of necessity be larger than the opening. Such an arrangement was used for the Tektite program where the habitat was lowered to the seafloor slightly overpressurized (Fig. 5-15). Once the habitat was on the bottom, the pressure inside was reduced to about 0.5 psi (0.04 kg/cm^2) over the ambient pressure so no external pressure was exerted on the hatch. Other habitats, such as Hydrolab and Helgoland, had pressure vessels with external as well as internal hatches (Figs. 5-16, 5-17). When a habitat is subject to both internal and external pressures,

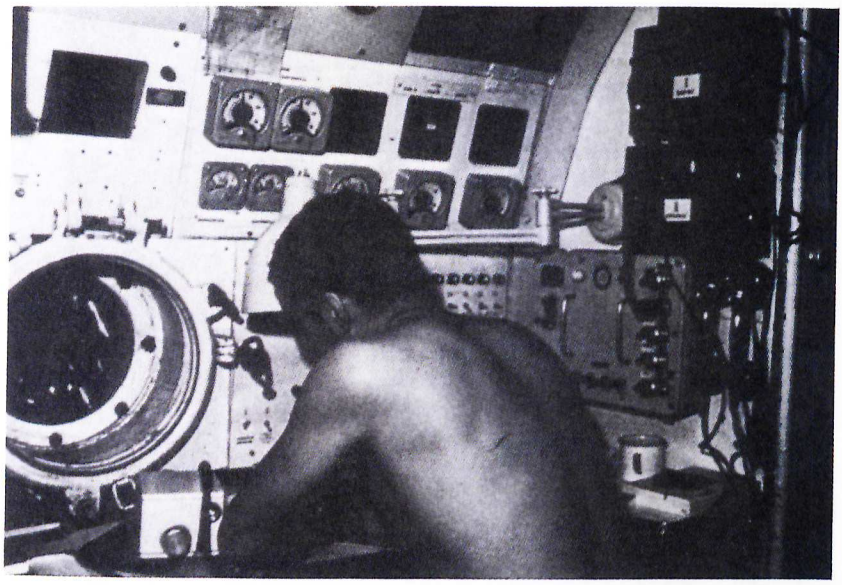


Figure 5-13. Interior of Chernomor II habitat showing flat port. (*Courtesy of Institute of Oceanography, Varna, Bulgaria.*)

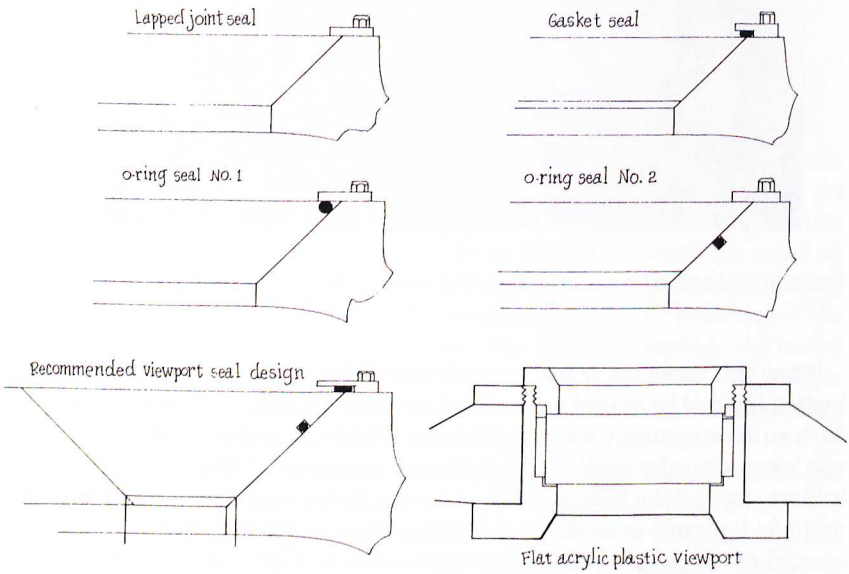


Figure 5-14. Examples of designs of ports used in undersea habitats. (*After R. Busby, 1976, Submersibles, Office of the Oceanographer of the Navy, Alexandria, Va., pp. 260–261.*)

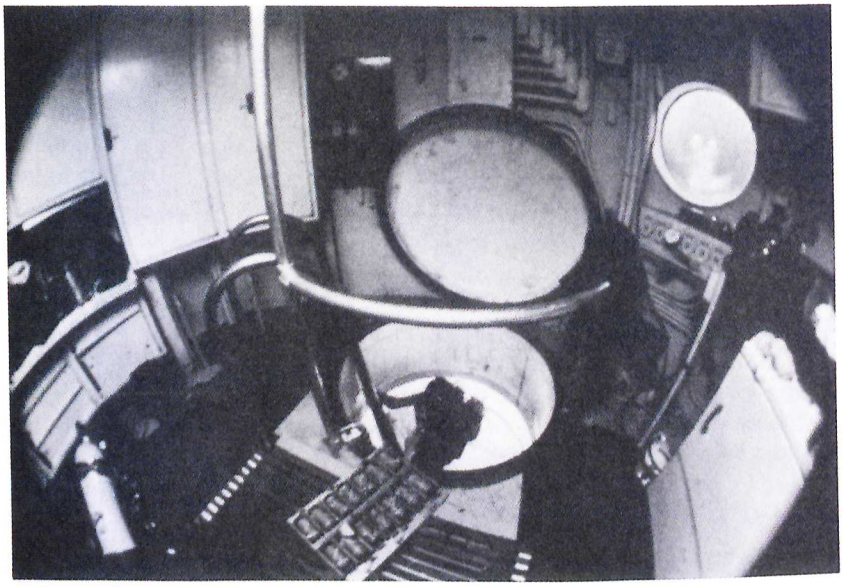


Figure 5-15. Hatch used for Tektite. (*Courtesy of General Electric Company.*)



Figure 5-16. Hatch system used for Hydrolab. (*Courtesy of William High, National Oceanic and Atmospheric Administration, Seattle, Washington.*)

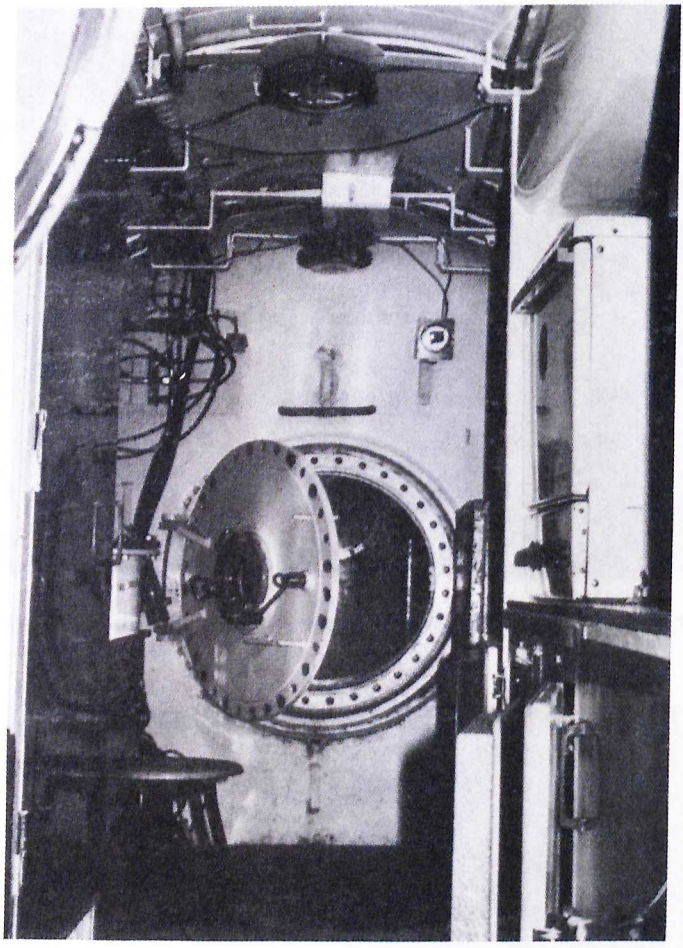


Figure 5-17. Hatch system used for Helgoland. (*Courtesy of GKSS, Bonn, Germany.*)

the best solution is to have a pressure-sealing hatch on both sides of the opening. If this is not possible, a movable locking mechanism is required, strong enough to withstand the shear forces generated by pressure on the hatch surface (Penzias and Goodman, 1973, p. 455): "This can be achieved by a breech-lock type of closure, or the radially expanding, cylindrical plungers often used on doors of bank vaults. In designing the seal for such a cover, the distortions of the pressure vessel during pressure and temperature cycles must be allowed for."

The advantage of designing for external and internal pressure is that the resulting habitat pressure vessel can be used for decompression while on the surface as well as on the seafloor, thus adding great flexibility to the system. Another advantage is that a double hatch system gives aquanauts inside the chamber added protection against premature opening of the hatch. This is a real plus when it is remembered that a pressure differential of only 1 psi (0.07 kg/cm^2) exerts a force of slightly over 700 pounds on a 30-inch (76.2 cm) hatch cover.

ENTRANCE TRUNKS

Location, size, and configuration of entrance trunks deserve special consideration. It is here that life-sustaining breathing gases give way to the cold ocean waters. In almost every habitat program, a near-fatal accident has occurred at or around the entrance.

Entrance trunks differ from hatches in that they do not always have pressure-tight integrity. There is a great variation in size, ranging from the 32-inch (81.3 cm) entrance for Hydrolab (Fig. 5-16) to the 5×10 foot (1.5×3.1 m) opening for La Chalupa (Fig. 4-45). The manner in which entrance is made by the aquanauts also varies greatly. Hydrolab's aquanauts had to ditch their scuba equipment in the water, swim a few feet to the entrance, and climb a ladder (Fig. 5-18). By contrast, in La Chalupa, aquanauts simply swam out of the water and sat on a large grating without taking anything off (Fig. 5-19).

Entrances such as Hydrolab's, where the aquanaut is required to climb a ladder, present a difficult task to aquanauts wearing diving equipment even under the best of conditions. If divers are injured or incapacitated, the job of getting them into the habitat is almost insurmountable. Further, the necessity of climbing a ladder complicates resupplying the habitat and passing equipment in and out of the water.

The Tektite habitat had a 4-foot (1.2 m) entry trunk that was ample in diameter, but when coupled with the requirement for an almost 10-foot (3.1 m) climb when entering and leaving the water, beginning and ending a dive was not easy (Fig. 5-20). Tektite's entrance was complicated further because the aquanaut first had to enter a shark cage for access to the entry trunk as was also required for Sealab II, (Fig. 5-21). By contrast, when entering the Helgoland habitat, the diver entered a trunk and surfaced directly into the wet room without climbing a ladder (Fig. 5-22).

Another design consideration for habitat entrance trunks is the variation of water level in the trunk due to tidal action and/or sea states. Changes in water level affect pressure in the habitat and the volume of air in the wet room. Also, if the wet room is large and significant changes in

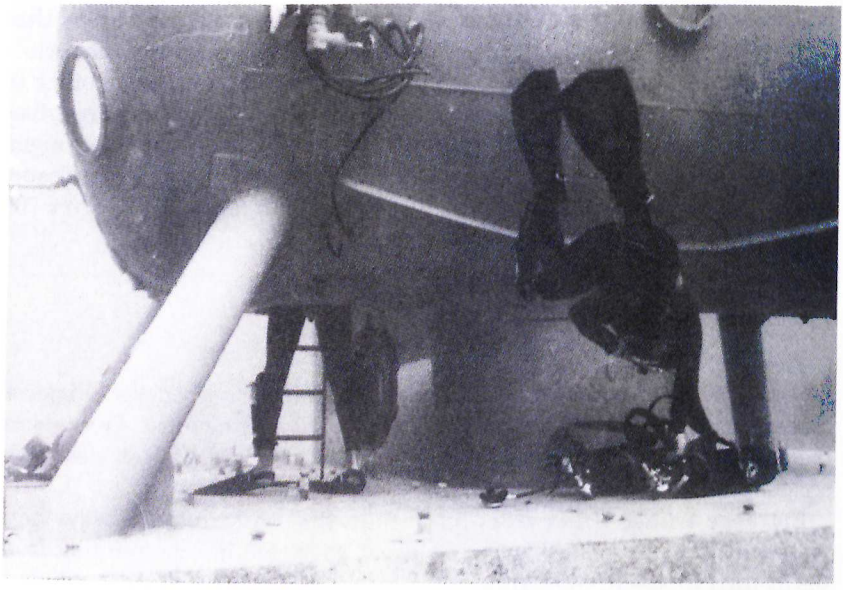


Figure 5-18. Aquanauts ditching diving gear prior to entering Hydrolab. (*Courtesy of William High, National Oceanic and Atmospheric Administration, Seattle, Washington.*)



Figure 5-19. Entrance and wet room of La Chalupa habitat. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

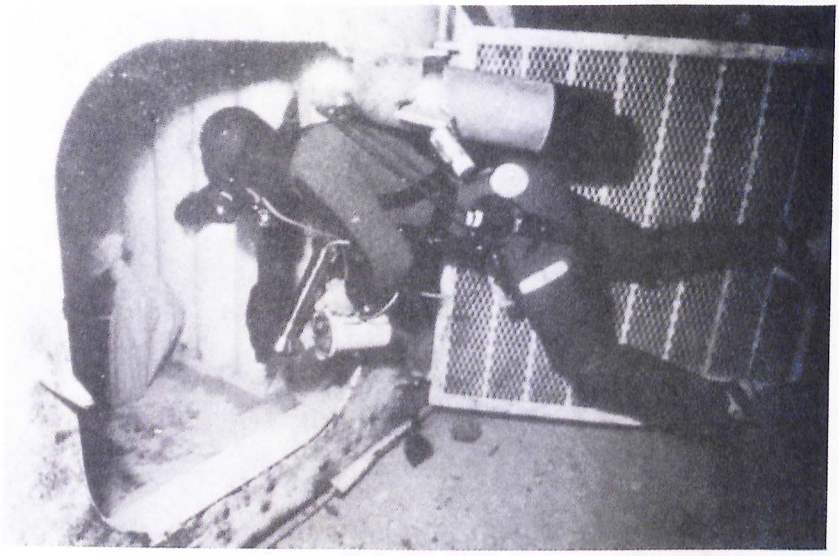


Figure 5-20. Entrance trunk showing ladder used for Tektite. (*Courtesy of General Electric Company.*)

water level are experienced, the resulting change in buoyancy can affect the stability of the habitat if there is not sufficient ballast.

Considering that most habitats had only one entrance, it is surprising that the problems surrounding the entrance were reintroduced time after time, as if by design. In each program with which we are familiar, the seafloor studies were interfered with, accidents nearly occurred, equipment was dropped, and specimens were lost.

The designers of future habitats should keep in mind that entrances to habitats should provide easy access to the wet room without the use of ladders or requiring divers to ditch their equipment in the water. Entrances



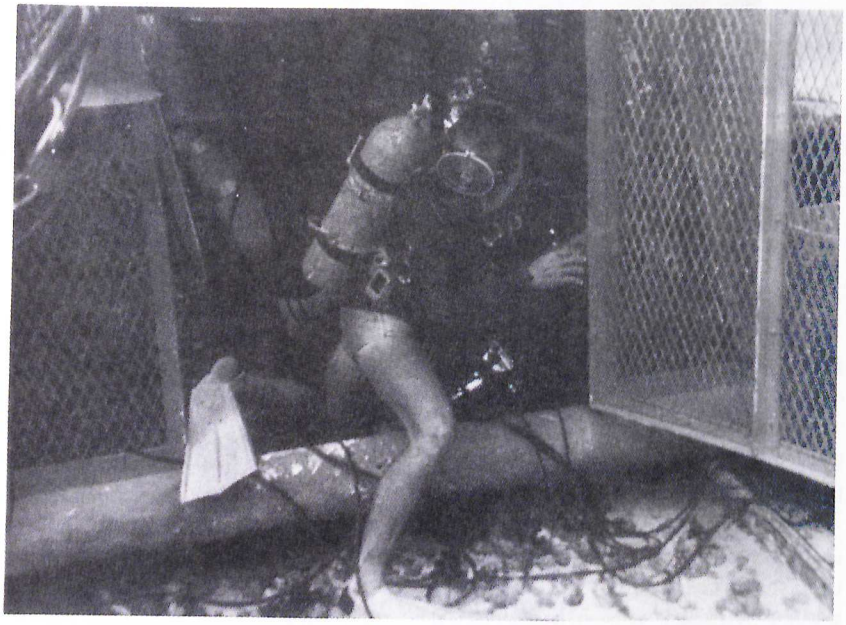


Figure 5-21. Aquanaut entering shark cage to reach Tektite entrance trunk (*photo by Ian G. Koblick*) and leaving shark cage in Sealab II (*official U.S. Navy photograph.*)

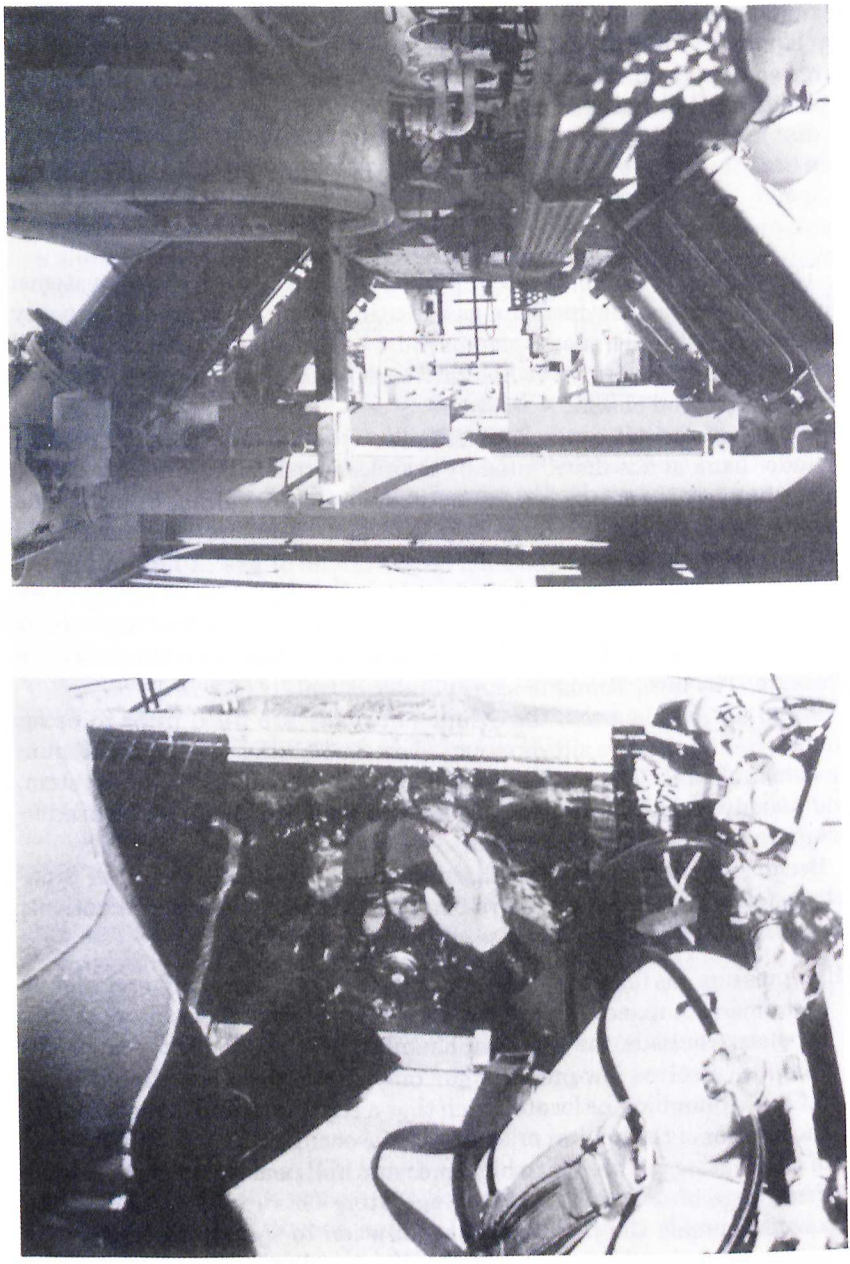


Figure 5-22. Entry trunk and wet room entrance in Helgoland habitat. (*Courtesy of GKSS, Bonn, Germany.*)

should be located in areas separated from dry rooms and not be blocked by equipment at any time. For reasons of safety, entrances should be large enough to admit at least two divers at one time and facilitate entry by an injured or unconscious diver.

PLUMBING

The habitat plumbing system may be divided into five subsystems: high-pressure gas, low-pressure gas, venting, sanitation, and emergency gas supply. Although these systems must be considered within an overall context during design of a habitat, each subsystem requires its own maintenance and checks.

High-pressure gas generally is supplied from a compressor or storage cylinder bank and is distributed by stainless steel tubing well protected from abrasion or rupture caused by wave action or falling objects. The storage bank consists of large high-pressure cylinders that have been manifolded together to maintain a large volume of gas at high pressure. Storage pressure varies from 1800 to 5000 psi (126.6 to 351.6 kg/cm^2). These cylinders usually are tested hydrostatically at 1.5 or 1.66 times service pressure and have a burst pressure of at least two times service pressure. The most common size cylinder is 240 ft^3 (6.8 m^3).

When air is to be used, the cylinders usually are filled prior to being transported to the dive site or mounted on the habitat. The high-pressure system is used to fill scuba tanks, serve as an emergency backup system, and usually includes a stepdown valve and regulator so it can be used to resupply the low-pressure system.

Because the technology is well established, the safety record of properly installed high-pressure gas systems has been good. Several precautions, however, can be taken to increase the margin of safety:

High-pressure gas lines should be run outside a pressure chamber designed for human occupancy. If possible, step-down pressure regulators should be placed outside the pressure chamber so that the interior of the chamber receives low-pressure gas only. In no instance should high-pressure plumbing be located such that a rupture would overpressurize the interior of the habitat or endanger the occupants. A simple method of eliminating the need for a high-pressure hull penetration is to use the first stage of a standard scuba regulator. This regulator should be located outside the chamber. The exception to this is the emergency high-pressure scuba cylinder inside the chamber.

All high-pressure tubing should be secured carefully to reduce the possibility of chafing or abrasions.

Any high-pressure tubing exposed to damage while loading supplies, transporting the habitat, or during routine maintenance should be protected by an outer casing.

It is important that high-pressure gas systems contain an adequate number of shutoff valves. For safety reasons, most regulators contain a burst disc or relief valve to relieve gas pressure but generally are not intended to function as shutoff valves over long periods. When a system is closed down for more than a few hours, it is desirable to close a shutoff valve upstream of the regulator to relieve the pressure load. Valves should be selected based on the type of connection, mode of actuation, gas to be used, size, temperature, and working pressure.

The low-pressure gas system provides the breathing gas for the aquanauts while in the habitat. It is designed to add gas to the habitat environment as determined in advance and to maintain sufficient pressure to keep water in the entrance trunk at a safe level.

For shallow-water habitats, the gas usually is provided from a low-pressure air compressor located either in a life-support buoy on the surface over the habitat, on a surface-support ship, or on shore (Fig. 4-16). In the case of deeper habitats such as Aegir and Sealab II, the low-pressure gas supply system carried helium and oxygen and was supplied from high-pressure storage banks located on a surface-support ship, with an emergency supply aboard the habitat. Both low-pressure and high-pressure gas supply should have a check valve at the habitat to prevent loss of stored gas in the event of a line rupture.

The venting system usually is composed of large-diameter, low-pressure hose or piping, sized to achieve the desired cycling time for ballasting and deballasting. The blow system can be supplied from the low-pressure system with backup from the high-pressure system.

The water-supply system is designed primarily to carry fresh water from the supply reservoir to the sinks and/or shower and to evacuate waste water. When water is stored on board, the low-pressure air system can be used to pressurize the water tanks, thus eliminating the need for a water pump.

INSULATION

As with any other structure, the type and amount of insulation required for the hull of an undersea habitat is determined by the nature of the surrounding environment. In general, it is desirable to have insulation of some kind regardless of the ambient water temperature to minimize condensation on interior walls and overhead surfaces. Elimination of this

moisture, in addition to reducing the humidity, relieves the cold and clammy feeling one gets when water is visible on the walls.

When selecting the type and amount of insulation for habitats, the composition of the breathing gases to be used must be considered. Experience has shown that when air or nitrogen-oxygen is used as a breathing gas in the habitat, aquanauts feel comfortable at a temperature between 75° and 80°F (23.9° and 26.7°C). On the other hand, when helium-oxygen mixtures are used, the fact that the thermal conductivity of helium is about six times that of air requires that a cabin temperature of close to 90°F (32.2°C) be maintained for comfort.

Depending on the location, insulation also may be required for cooling purposes. For example, a habitat that is to remain on the surface for extended periods of time in tropical areas with the aquanauts inside such as for decompression should be insulated to protect them against high interior temperatures. Many aquanauts have found that decompression in a habitat that was comfortable on the seafloor turned into a slow cook in the sun. We had to endure 49 hours of over 100°F (37.8°C) temperatures plus 100% humidity in such a situation. Unless these circumstances are encountered, the use of insulation for its thermal properties alone may not be required. For example, the Tektite habitat was used in the Caribbean where the water temperature at the operational depth of 50 feet (15.2 m) was about 78°F (25.6°C). An active cooling system was required to remove heat generated by the aquanauts and equipment. A cabin heat exchanger served each compartment, and thermostats were provided to permit control of temperature within a range of 75° to 90°F (23.9° to 32.2°C). By contrast, the Sealab II habitat operating in the 42° to 55°F (5.6° to 12.8°C) waters of California with a helium environment required considerable insulation and a heating system. Insulation used was navy standard stock submarine, 1-inch (2.54 cm) thick corkboards on the overhead and 2 inches (5.1 cm) on the sides. Since radiant heating cables were used in the concrete deck, no insulating material was required except carpeting (Pauli and Clapper, 1967).

Insulation may be applied to the inside or outside of a habitat. In addition to providing the required insulation value, the material must be nonhydroscopic, nontoxic, nonodor absorbing, noncrushing under pressurization, and decompressible, and it must retain its properties in a helium atmosphere (University of New Hampshire, 1972).

Effectiveness of internal insulation decreases when interior walls, pipes, floors, and other parts in metal-to-metal contact with the hull cause a thermal short circuit to the outside. In addition, interior walls usually are covered with brackets, cabinets, ducts, and other objects that make effective installation of the insulation difficult. In such cases, external-mounted insulation may be preferable.

Because the mass of insulating material is likely to be substantial if placed inside the habitat, the risk of fire also must be considered. While the danger of fire may be minimal on the seafloor because of reduced oxygen content in the breathing gas, habitats in which aquanauts are decompressed present a potential fire hazard. One type of suitable insulation is a closed-cell elastomer foam in ¼- to ⅜-inch (0.64 to 0.95 cm) thick sheets treated with fire retardants. Others are polyvinyl chloride or syntactic foam. Such insulation can be applied as tiles or sheets or can be sprayed on, depending on habitat requirements and configuration. A number of products now on the market are light, rigid, incombustible, and impervious to water vapor and gases.

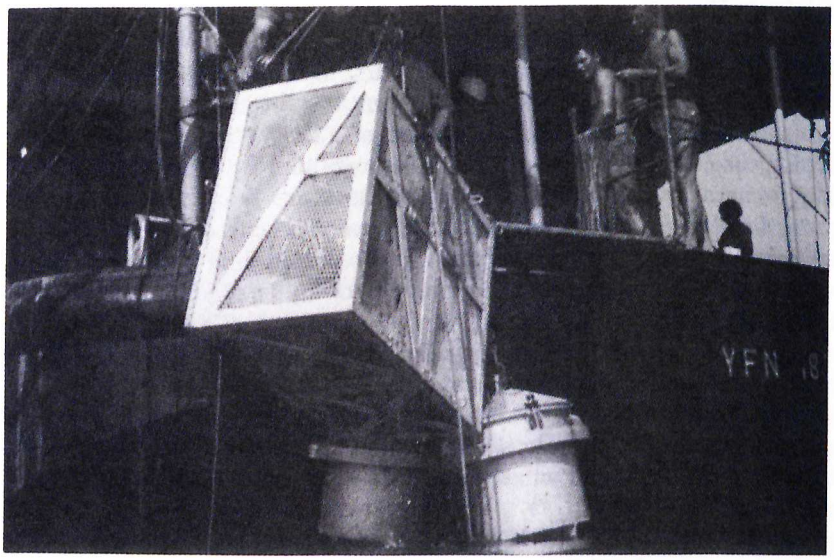
In summary, insulation has been found to be desirable, even in tropical areas, to reduce interior condensation while on the seafloor and for cooling when the habitat is on the surface. Factors to be considered in selecting insulation include the breathing gas, fire hazards, internal or external insulation, and whether a cooling system also will be used.

DRY TRANSFER SUPPLY SYSTEMS

A design feature of many habitats that often was neglected during initial planning was the method of transferring dry material to and from the habitat. In spite of the most meticulous advance planning, there is always a need for the transfer of items such as scientific equipment, specimens, spare parts, garbage, mail, birthday cakes, and the like that must be kept dry.

In many habitats, loading and unloading dry transfer supplies was perhaps the most time-consuming, sometimes dangerous, exhausting task faced daily by the aquanauts. In more than one program, effort consumed in transferring supplies detracted significantly from carrying out the scientific projects. Many different systems have been tried, ranging from plastic bags to sophisticated pressure pots. Usually a pressure pot was loaded on the surface and brought to the habitat by surface-support divers or lowered on a line. Once on the bottom, the pot had to be transported to the habitat and then raised through the trunk using a winch of some kind. Lead weights often were added to the contents to bring the pot close to neutral buoyancy to facilitate the work of the aquanauts. The task of handling these pots was the most hated, frustrating, temper raising of all mission jobs.

Transfer pots range in size from the very large pots used in Sealab II to containers holding only about 3 gallons. In several cases, the pots used were commercially available pressurized spray paint containers. Figure 5-23 shows transfer pots used for six habitat programs. In each case, the



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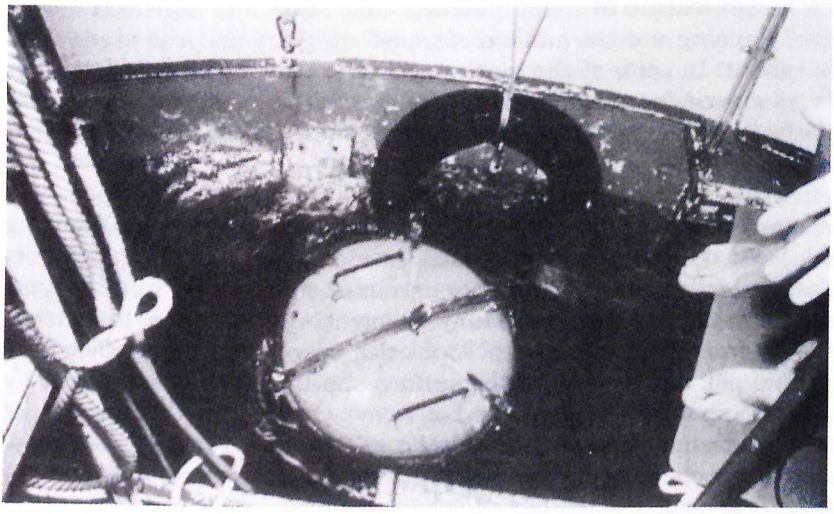
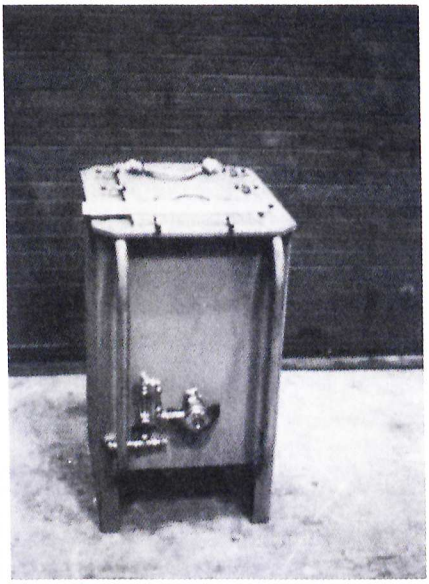


B

Figure 5-23. Transfer pots used for six habitat programs. *A:* Sealab II (*official U.S. Navy photograph*); *B*: Helgoland (*courtesy of Society for Nuclear Reserach in Ship-Building and Navigation, Bonn, Germany*); *C*: Aegir (*photo by James W. Miller*); *D*: Tektite (*official U.S. Department of the Interior photograph*); *E*: Hydrolab (*courtesy of Robert Given, Catalina Marine Science Center, Avalon, California*); *F*: La Chalupa (*photo by Ian Koblick*).

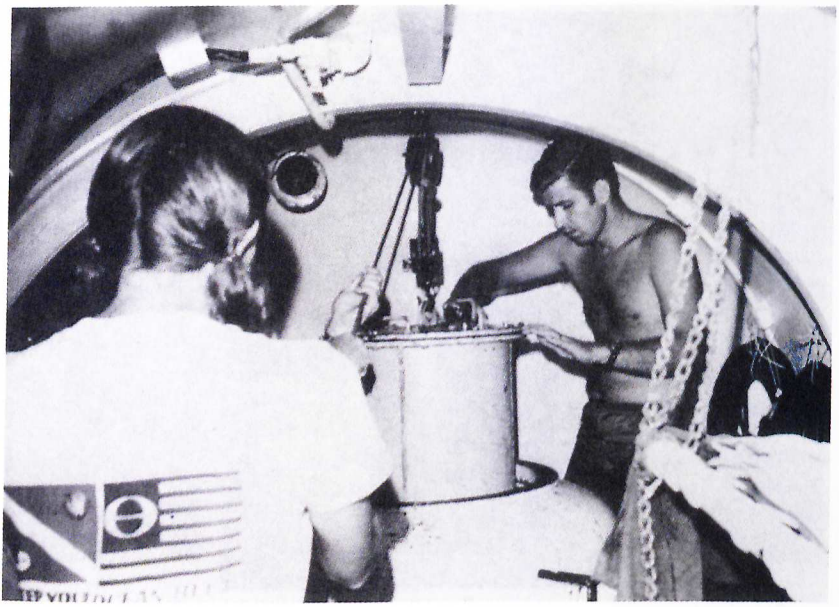


C



D

Figure 5-23. *(continued).*



E



F

Figure 5-23. *(continued).*

pot had a pressure relief valve to enable it to be opened both on the surface and in the habitat. A rigid procedure was necessary to ensure that the lid was tightly sealed for each transfer. Even with such precautions, many meals and expensive pieces of scientific equipment were ruined due to a leaky pot.

Although pot drops are a necessity, good planning can reduce the frequency significantly. The La Chalupa habitat was designed to reduce the need for pot transfers to a minimum. This was achieved, in part, through the use of a trash compactor, which reduced trash removals to once or twice a week. In addition, all scientific equipment was loaded aboard the habitat on shore prior to towing it to the operational site. One cause of frequent pot transfers in several habitats was the replenishment of CO_2 absorbent material. Therefore, when designing the life-support system of a habitat, consideration must be given to transfer problems when selecting a CO_2 absorbent.

There is no simple solution to the dry transfer problem. It is an example of a situation in which prevention is the best cure. In the future, dry transfer systems should not be an afterthought but must be considered as an essential part of the system, beginning in the initial planning phases.

HABITAT TRANSPORTATION AND EMPLACEMENT

The initial selection of the operational site is determined by the overall goals of the program. Once these are identified clearly, other factors of prime concern include local topography, weather, tides, currents, water temperature, and type of bottom. In addition to those environmental considerations are logistics, availability of local suppliers and labor, local transportation, communication, and emergency evacuation systems. Each of these factors affects the process of transporting a habitat and readying it for seafloor occupation.

Historically, transportation and emplacement of habitats have been achieved with considerable difficulty. Many habitats were too unwieldy to move overland, often too heavy to handle with readily available cranes, too large or cumbersome to transport on available ships, and/or too unseaworthy to tow in the open ocean. Regardless of the mode of transportation, once the habitat arrives on site, the operations team is faced with the formidable task of lowering it to a preselected location on the seafloor in a stable manner and with no damage to people or equipment.

One rather elaborate method of emplacing a habitat is to transport it to the site on a large ship, lowering it over the side using large cranes or floating it out of a floating dry dock. In either instance the habitat is

relatively protected during transport and usually needs only a short tow to the site.

The Tektite habitat, designed in part to simulate a space capsule, was almost impossible to tow even for a short distance because of its two vertical cylinders and the large rectangular base, plus the fact that it had a draft of about 16 feet (4.9 m). Figure 5-24 shows Tektite being loaded onto a U.S. Navy floating drydock (LSD) at the Philadelphia Naval Shipyard and being offloaded at the operational site in the Virgin Islands. This arrangement required only a short tow of about a quarter of a mile (0.4 km). Even this short tow required the use of side-mounted lift bags.

The emplacement of the Tektite habitat, while carried out safely on two occasions, was extremely complex. It required floating cranes, special

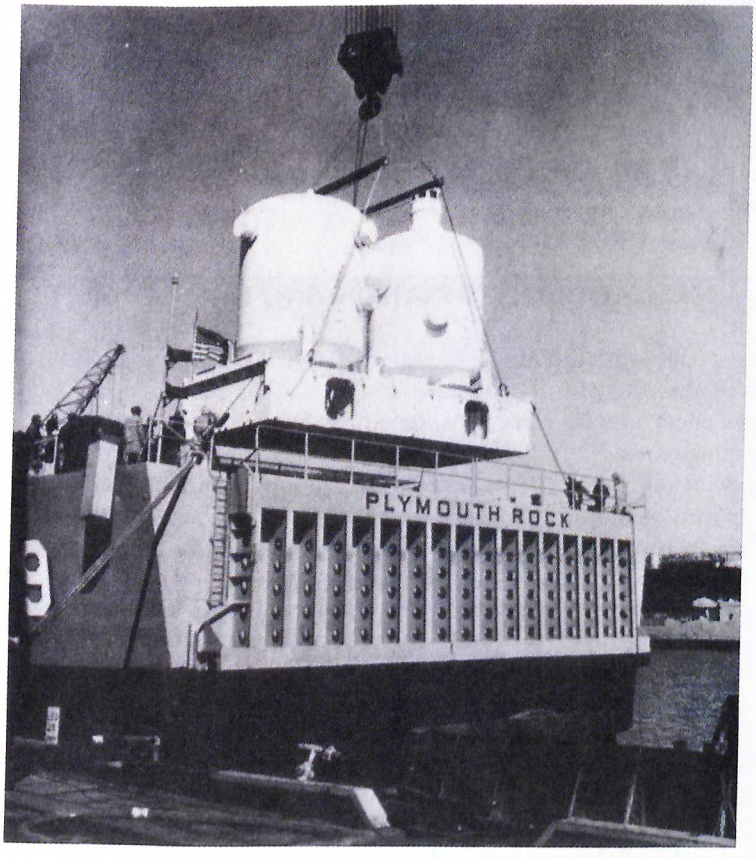


Figure 5-24A. Tektite habitat being loaded (*official Department of the Interior photograph*).

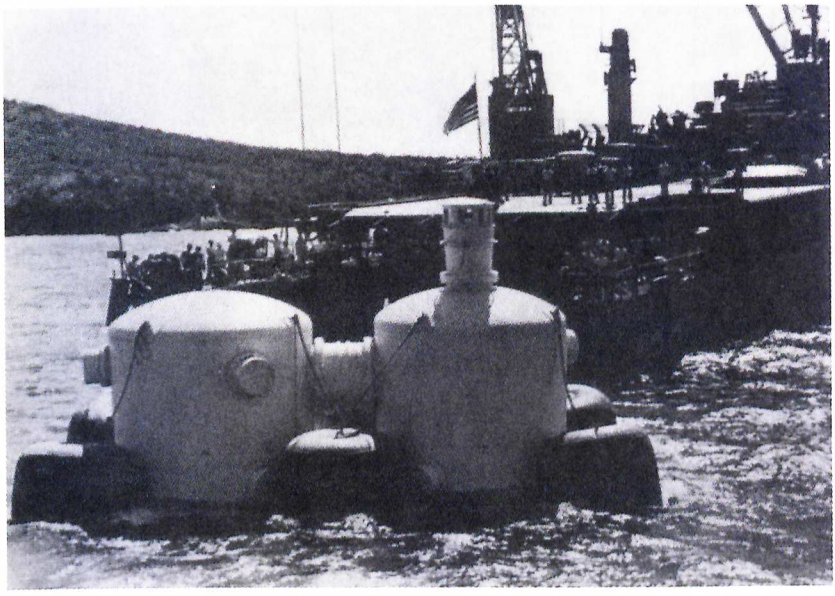


Figure 5-24B. Tektite habitat being offloaded (*Courtesy General Electric Company*).

leveling tools, and the movement and placement of large weights. Site preparation was extensive. An advance party had to place two 1000-pound (435 kg) concrete clump anchors for mooring the habitat temporarily while down-haul equipment was being attached. The seafloor had to be leveled and the sand bottom graded in much the same manner as a concrete slab is leveled during pouring.

Four 2,500-pound (1132 kg) anchor clumps used to haul the habitat down were lowered to the bottom by a crane and moved into position by construction divers using six 500-pound (227 kg) lift bags. With Tektite in its moor and floating at the surface, pig iron ballast was placed in trays to achieve stability and to give the habitat a negative buoyancy of 2½ tons when wholly submerged (Fig. 5-25). On completion of trimming operations on the habitat base, chain falls were attached to the anchor clumps.

Eight construction divers then hand winched the habitat 20 feet (6.1 m) to the bottom while spirit levels were used to measure levelness during submergence. When the habitat reached bottom, vent and flood valves on the ballast tanks were opened, and the habitat buoyancy changed from 2½ tons positive to 2½ tons negative. Twelve and one-half tons of ballast were lowered to the top of the habitat base and distributed by divers in the ballast trays. The habitat was repressurized periodically using the air

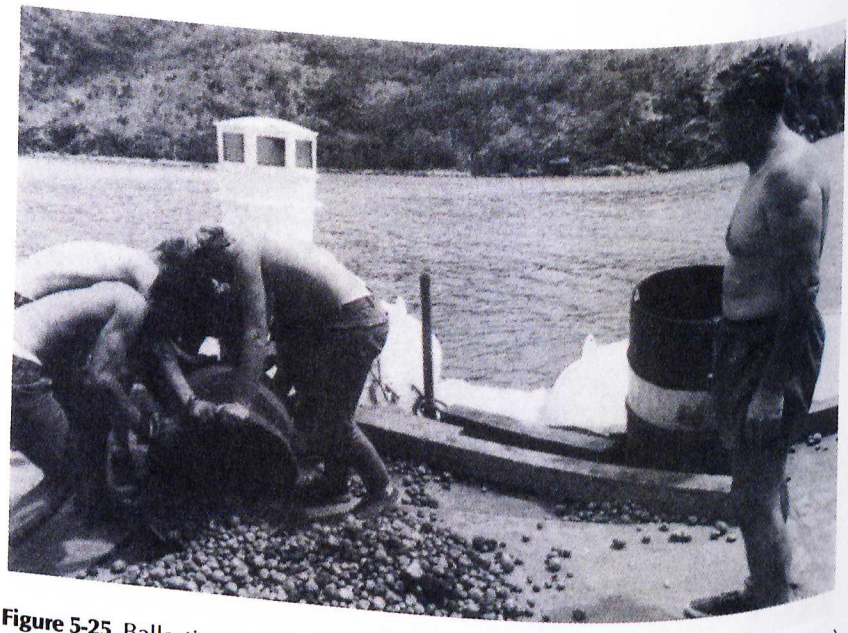


Figure 5-25. Ballasting Tektite II with pig iron. (*Courtesy General Electric Company.*)

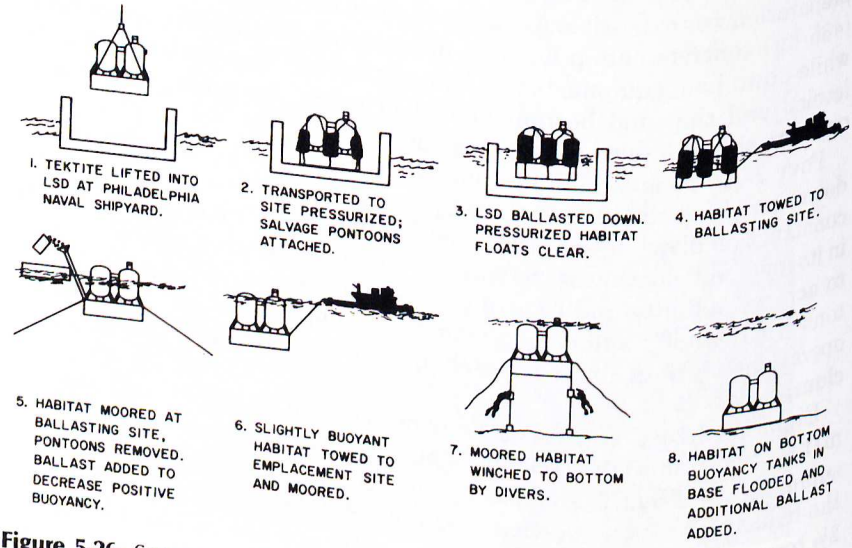


Figure 5-26. Summary of Tektite II emplacement procedure. Data derived from J. Miller, J. VanDerwalker, and R. Waller, 1971, *Tektite-2 Scientists in the Sea*, U.S. Department of the Interior, Washington, D.C.

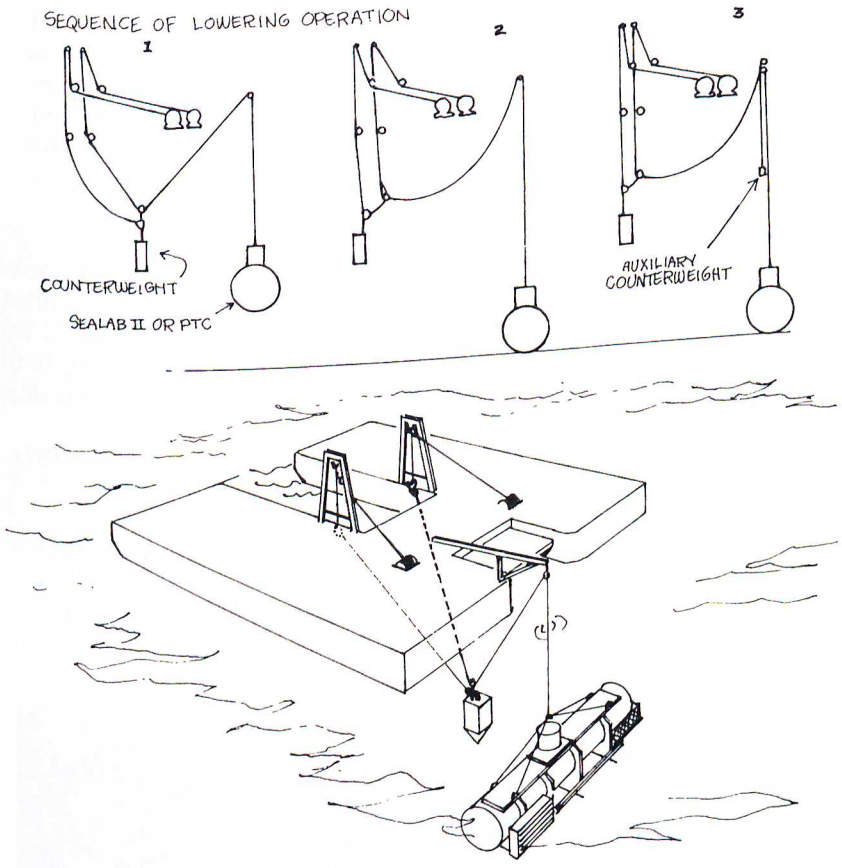
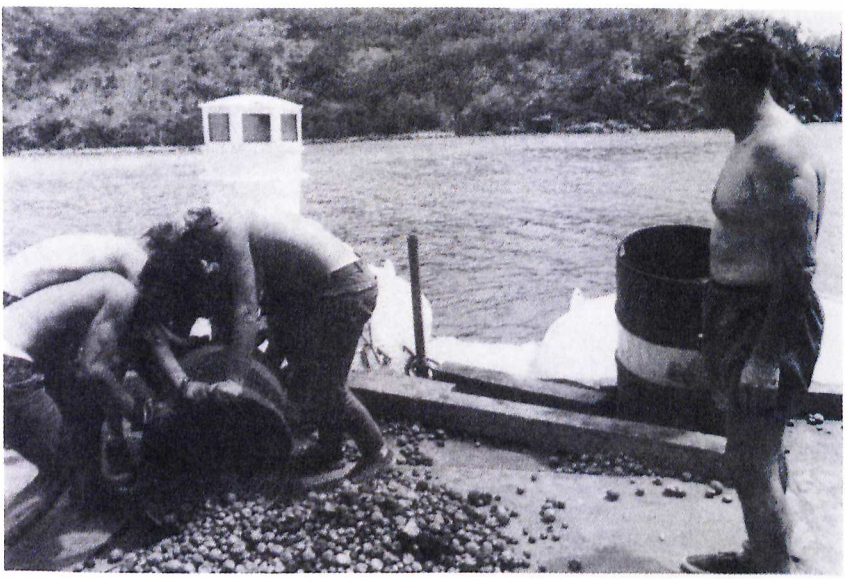


Figure 5-27. Sealab II emplacement procedure showing counterweight system. (After D. Pauli and G. Clapper, 1967, *An Experimental 45-Day Undersea Saturation Dive at 205 Feet, Project Sealab Report, Office of Naval Research Report ACR-124, Department of the Navy, Govt. Printing Office, Washington, D.C., p. 125.*)

compressor on the diving barge and checked for leaks. The total emplacement procedure for Tektite II took almost a full week to complete. A summary of the emplacement procedure for Tektite II is depicted in Figure 5-26.

Another example of a complex emplacement and trim system is found in the 1965 Sealab II program (Fig. 4-2). The general sequence is depicted in Figure 5-27. Pauli and Clapper (1967, p. 327) describe some of the problems encountered with this system:

> In actual operation, certain problems developed in using the system as designed. First, when the end overhead tanks were flooded on the surface,



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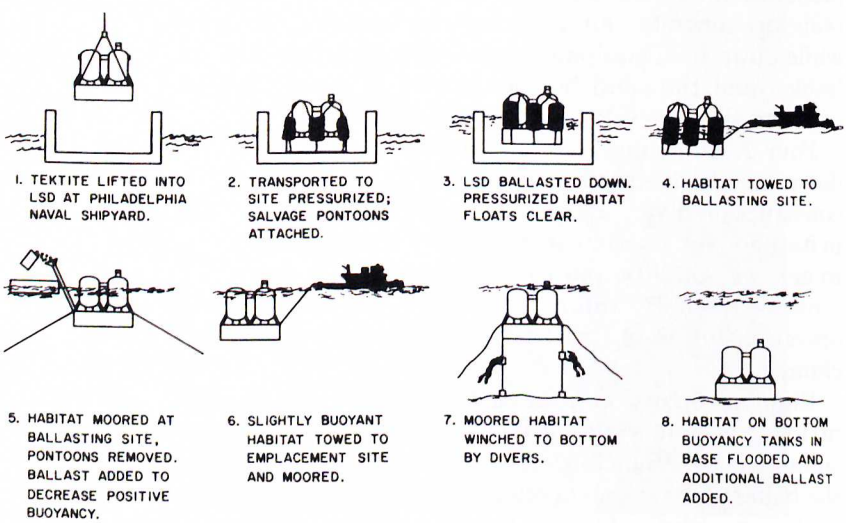

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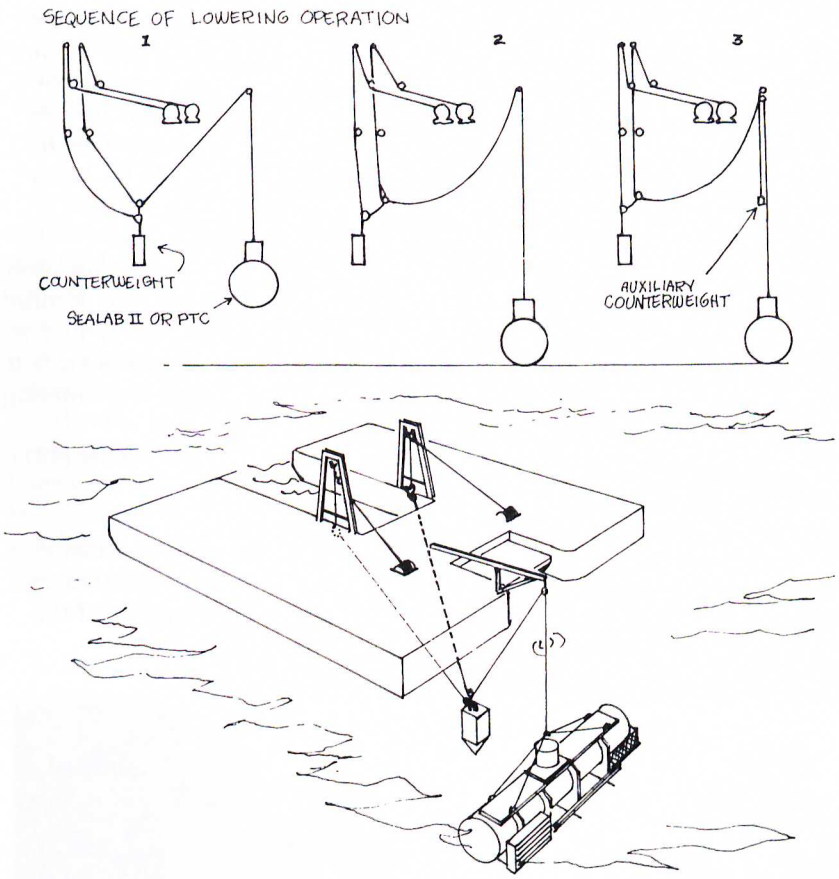

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> In actual operation, certain problems developed in using the system as designed. First, when the end overhead tanks were flooded on the surface,

trim was difficult to control. These tanks flood independently, and one tends to fill faster than the other. As it does so, that end trims down, increasing the head on the flood valve, accelerating the out-of-trim conditions. Ultimately, the flood valve on the high end broaches and the tank will not fill further. When this happened, the tank on the high end was filled by hand from buckets. In the future, provision should be made for better control of flooding of longitudinally flooded tanks.

A classic example of a poor design creating severe launching problems also occurred during the Tektite II program when the Minitat was launched. This vertically configured habitat (Fig. 4-24) had its own design problems related to a high center of gravity, causing it to be unstable under tow in moderate seas and also during the lowering process (Fig. 5-28).

The problem was described by Miller, VanDerwalker, and Waller (1971, p. III-13):

> The system proved to be unstable because of a shift between the center of gravity and the center of buoyancy when passing through the air/water interface. The instability resulted in an uncontrolled heeling-over of the



Figure 5-28. Minitat habitat during emplacement. (*Courtesy of David E. Adkins, Hydrotech, Houston, Texas.*)

pressure vessel until its buoyancy took effect. This generally resulted in the pressure vessel assuming a 45 degree angle at either one of four quarters. The heeling motion did not constitute a severe problem because a correct attitude could be established soon after it occurred by additional flooding of the pontoons. It did appear ungainly, however.

In another instance, the initial launching of a habitat resulted not only in aborting the mission but also in abandoning the entire system (Heydorn and Addison, 1972). On May 21-22, 1972, outside Durban harbor, South Africa, the habitat HUNUC (Habitat University of Natal Underwater Club) was emplaced at a depth of 32.8 feet (10 m) without difficulty (Fig. 5-29). Because of delays due to winch problems, darkness overtook the operation before the habitat could be ballasted properly. Before divers could return the next morning, heavy seas had caused the habitat to break its moorings and move across the bottom, smashing into nearby limestone reefs. The basic problem was the lack of ballast coupled with a large sail area, as shown in Figure 5-29. In effect, the habitat was blown over by the high current. Damage was so severe that the habitat subsequently was stripped and abandoned.

The experiences of Minitat and HUNUC illustrate two cases in which



Figure 5-29. South African habitat HUNUC. (*Courtesy of Oceanographic Research Institute, Durban, South Africa.*)

programs were terminated because of launching problems that resulted basically from poor design.

Several habitats were designed such that a large cylinder was mounted on a ballasted support structure along with a myriad of other equipment that allowed the system to be towed for short distances at very slow speeds. Because most of these programs took place within a few hundred yards of shore, this usually did not present a problem in good weather. Examples of habitats falling into this category include Helgoland (Fig. 4-36), Seatopia (Fig. 4-32), and Chernomor (Fig. 5-30). Each of these systems, while towable, had protruding and exposed fixtures and miscellaneous equipment that were highly susceptible to being damaged during the towing operation (Fig. 5-30). By contrast Cousteau's Conshelf III habitat had clean lines with no protruding equipment (Fig.4-8) and towed very low in the water (Fig. 5-31.)

Because of its successful use over a span of 13 years, let us look at the emplacement procedure used for the Hydrolab habitat in more detail. As with other habitats, Hydrolab was towable for short distances in relatively calm seas. Its horizontal configuration and top-mounted floodable ballast tanks allowed it to float in a stable position. It had ballast

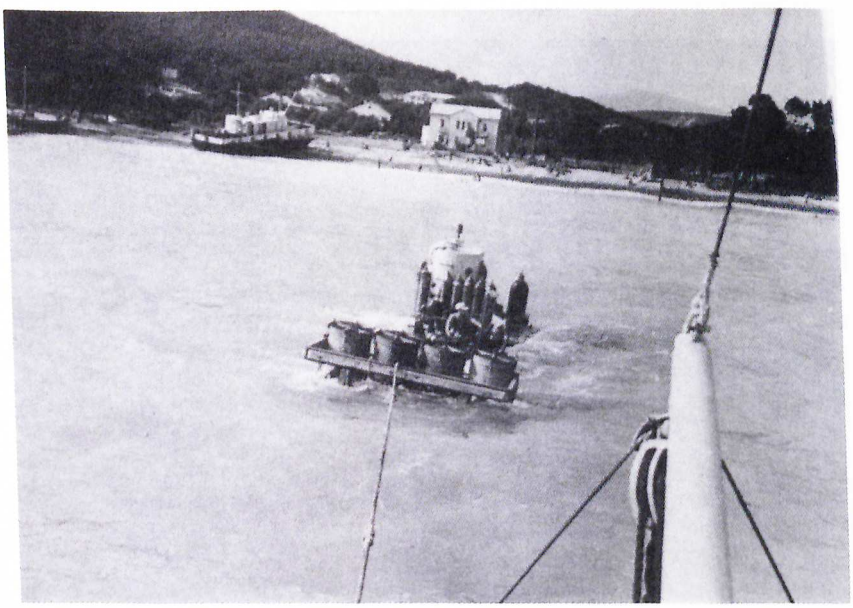

Figure 5-30. Chernomor habitat under tow. (*Courtesy of Institute of Oceanography, Varna, Bulgaria.*)



Figure 5-31. Conshelf III habitat under tow in Monaco Harbor. (*By Bates Littlehales; © 1966 National Geographic Society.*)

attached to the legs that protruded 4 to 6 feet (1.2 to 1.8 m) below the pressure cylinder, resulting in a draft of about 8 feet (2.4 m) (Fig. 4-14). The drag created by these legs, however, limited the towing speed of the habitat to 1.5 knots. Once on site, Hydrolab was submerged by flooding ballast compartments, which required approximately 3 or 4 hours from the time valves were opened until the habitat was ready for occupancy, a procedure requiring only two divers. A limiting feature of Hydrolab was the need for a fairly level bottom because the base was a concrete slab that did not allow any adjustment for an uneven seafloor. Although Hydrolab was moved occasionally for special missions, most of its four years at Grand Bahama Island and the years at the St. Croix site in the Virgin Islands were spent at a single location.

One of the few habitats designed specifically for towing was Aegir (Fig. 4-39). Because it was mounted on a pontoon structure, there was sufficient buoyancy to transport it completely out of the water (Fig. 5-32). Aegir could be towed at speeds up to 8 knots in seas of 3 to 4 feet (0.9 to 1.2 m). Once on site, it was attached to two moorings. The aquanauts inside the habitat then lowered two 1.5-ton weights to approximately 30 to 50 feet (9.1 to 15.2 m) below the keel of the pontoon barge. Surface-support divers then opened flood and vent valves on the deck of the barge, which



Figure 5-32. Aegir habitat being towed by support ship *Holokai*. (*Courtesy of Makai Range, Inc., Honolulu, Hawaii.*)

initiated flooding of the main ballast tanks. When this work was accomplished, only about 3 feet (0.9 m) of the pressure chamber floated above the surface. At this point, submergence of the habitat was achieved by adding water to variable ballast tanks. Descent was halted temporarily 30 to 50 feet (9.1 to 15.2 m) above the seafloor when the weights hit bottom. Final emplacement was completed either by winching the habitat to the seafloor or by further flooding of the variable ballast tanks. The Aegir was recovered at the end of a mission by reversing the procedure. Main ballast tanks were not blown until the barge reached the surface. Provisions were made so that this operation could be accomplished using an external air supply in the event there was not sufficient air on board the barge.

Another habitat designed for mobility was La Chalupa (Fig. 4-41). Because the habitat was contained completely within a barge, plumbing and electrical systems were not exposed, as was the case with Aegir. La Chalupa was designed to be towed in seas up to 8 to 10 feet (2.4 to 3.0 m) and emplaced in 4-foot (1.2 m) seas. The barge had a draft of 6 feet (1.8 m) when rigged for towing and could be towed at speeds up to 6 knots.

On site, La Chalupa was secured with a single anchor. One support diver opened flood valves on the barge and within 10 minutes the barge

was flooded to a depth such that its decks were awash (Fig. 4-48). This speed was an important feature as it minimized surface time during which equipment could be damaged by wave action. At this stage, the habitat was 2.5 tons positively buoyant. A hard tank capable of adding an additional 2.5 tons of ballast was then flooded, causing the habitat to descend slowly in a level position to the seafloor. This level posture was the result of a design that ensured no air pockets remained in the barge. When the habitat reached the bottom, a support diver swam down and opened valves on the main water ballast tank inside the barge. With these tanks full, the habitat had a total negative buoyancy of 22 tons. Fig. 5-33 shows the buoyancy-control procedure for lowering La Chalupa. The habitat could be leveled on the bottom by adjusting the four hydraulically powered legs, permitting the habitat to sit in a level position on a slope with an inclination of 15°. When at dockside, the legs also could be used to lift the entire structure 2.5 feet (0.7 m) out of the water to permit maintenance, sand blasting, and painting. During towing, the legs were

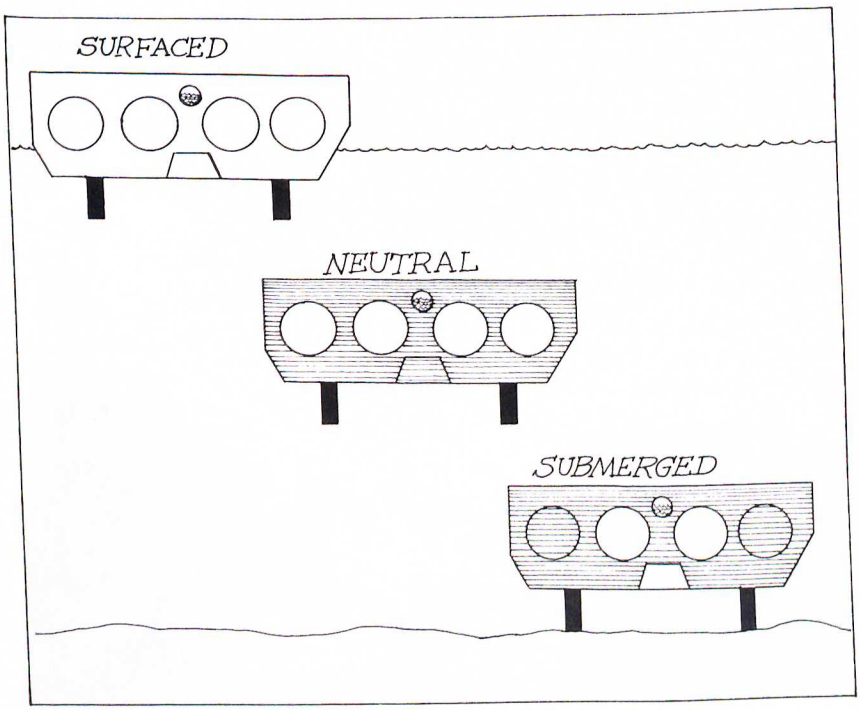

Figure 5-33. Buoyancy control during lowering of La Chalupa habitat. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

raised so their feet were almost flush with the underside of the barge. When fully emplaced on the seafloor, the entrance trunk was about 5 to 6 feet (1.5 to 1.8 m) off the bottom, allowing ample space for aquanauts to enter and exit the habitat.

La Chalupa is by far the easiest to tow and emplace of any other habitat constructed to date. It can be moved around easily in protected areas near shore by boats as small as an 18-foot (5.5 m) rubber boat. On one occasion, La Chalupa was towed in the open sea for a distance of 8 miles by a 24-foot (7.3 m) boat (Fig. 5-34). On another occasion, it was towed behind an 85-foot (25.9 m) work boat from Puerto Rico to Florida, a distance of 1200 miles (1930 km).

Whether aquanauts remain inside during recovery depends on design of the pressure vessels. The Helgoland, Aegir, and La Chalupa habitats were designed so that the aquanauts could remain under pressure during recovery. Although Hydrolab also permitted decompression in the habitat, it never was recovered with aquanauts under pressure. Probably the most convenient system was Aegir, which allowed aquanauts to control the ascent of the habitat from inside. A major advantage of keeping aquanauts inside during recovery is that the problem of transferring them to a heaving support ship or barge is avoided, and they are maintained in a controlled environment until decompression is completed.

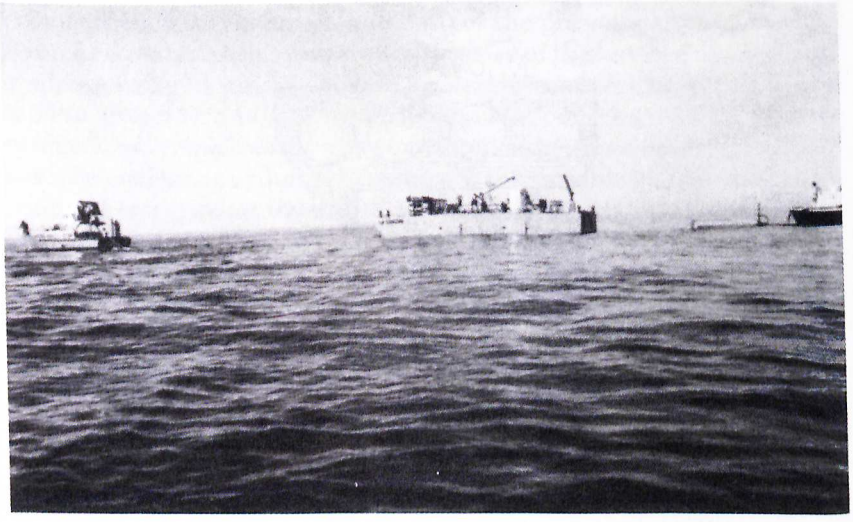

Figure 5-34. La Chalupa habitat under tow. (*Courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

Clearly habitats should be designed with towing and emplacement in mind unless they are to remain permanently in one location. If towing is a requirement, enclosing all plumbing, penetrators, pressure vessels, and electrical systems inside a watertight barge to reduce drag and protect these systems while under tow is desirable.

The configuration of an underwater habitat affects not only its towing characteristics but also its stability and ballasting requirements. As with any other seagoing structure, the center of gravity must be such that there is no danger of capsizing while under tow, even in moderately heavy seas. Positive buoyancy, stability, and adequate freeboard must be maintained while the habitat is moored at the operational site, as well as while being towed, particularly important if a top entry hatch must be open at this time (wave action could cause flooding.) Sufficient negative buoyancy must be provided during lowering to maintain stability but not so much as to overload lowering gear or cause an uncontrolled descent. Once the habitat is on the bottom, negative buoyancy must be adequate to provide stability during heavy seas and to compensate for blowing water out of entry trunks.

The lack of sufficient ballasting once on the seafloor has been the cause of severe problems in several habitat programs. In addition to the misfortunes of the Minitat and HUNUC, the most serious mishap of all occurred during the Chernomor program where, because of insufficient ballast, the habitat washed up on the beach with five men inside still under pressure.

SURFACE-SUPPORT EQUIPMENT

The basic functions of a surface-support system are to provide power, water, breathing gas, and communications. The most economical breathing gas system is a shore-based compressor that pumps a continuous flow of air into the habitat that exits via the entrance trunk in the form of bubbles. Such an open system can be used safely to depths of about 50 feet (15.2 m). The constant flow of fresh air reduces the likelihood of CO_2 buildup and also eliminates the need for a scrubber system. For habitats operating near shore, requirements for power, water, and communication also can be met by umbilicals.

While shore-based support has been used in several programs, habitats located beyond about 1 mile (1.6 km) from shore must be supported from a surface platform. The cost of long umbilicals and the operational hazards of extended lifelines make a greater distance impractical.

For small habitats, the basic life-support requirements can be met by an unmanned support buoy such as the Hydrolab program has used for years. This buoy (Fig. 4-16) is a 23-foot (7 m) boat hull containing a 16.5

hp diesel engine that powers a 7.5 kw generator, a low-pressure compressor, a high-pressure compressor, 250 gallons (946 l) of freshwater, a freshwater pump, air circulator fans, and 250 gallons of diesel fuel. This system will sustain the habitat for one month without refueling.

In addition to the low-pressure compressor used for supplying habitat breathing gas, a high-pressure compressor and/or storage bank is required to recharge scuba cylinders and bring the habitat to the surface in emergencies. A high-pressure gas system also can be used to replenish the low-pressure system. The La Chalupa habitat had 6000 cubic feet (170 cubic meters) of high-pressure air stored on board at a bleeding rate of 120 cubic feet (0.28 cubic meters) per hour. This storage bank could supply the habitat with breathing gas for 25 days if necessary.

Water supplies for a seafloor habitat can be met easily either from storage tanks located on a buoy or ship or from shore. All that is required is a properly maintained storage tank and an appropriate pump. Most habitats also contained an emergency supply of water on board.

Electrical power requirements of habitats range from about 10 to 100 kw depending on mission requirements and habitat design (University of New Hampshire, 1972). Power sources that meet this requirement include transmission lines from commercial utilities, diesel generators, closed cycle diesel systems, batteries, fuel cells, and nuclear plants. The most common power source for seafloor habitats is the diesel-powered generator because they usually are well built and are intended for use where emergency or standby power is required. Because they are used for vital life support in undersea systems, a backup generator should be available if the system is located on a buoy. If the generator is located on shore or on a ship, backup power is usually available from other sources.

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Chapter 6

Life-Support Systems and Operational Facilities

Life-support requirements of an underwater habitat basically are no different from those found in other human environments. Aquanauts need a breathing medium, food, water, thermal protection, and a system for waste management. As in any other situation in which living conditions are unusual, only the delivery system is different.

Even a cursory review of the sixty or so habitats built since 1962 reveals that most should be classed as survival shelters. The principal questions asked by those responsible for their design were: Can humans survive on the seafloor? Will the habitat leak? Is the breathing gas adequate? What are the psychological problems? How do we decompress safely? What are the long-term effects of pressure?

As technology advanced and our need to understand the oceans grew, simply surviving no longer was enough. The study of man and machine alone could not justify continuation of underwater programs. Survival, at least in the shallow reaches of the oceans, gave way to accomplishment of work in the fields of science, technology, and engineering. Although living and working in the sea always will present an element of danger, technical advances made with regard to life-support equipment, particularly with respect to reliability, have permitted aquanauts to devote their attention to matters other than personal safety and equipment maintenance.

While living in the sea always will require a certain spirit of adventure,

future underwater laboratories will need more and more to incorporate life-support systems such that seafloor programs will attract aquanauts whose primary goals are science and technology rather than solely experiencing a seafloor adventure. Such individuals will not want to spend time repairing equipment, transferring supplies, maintaining the environment, and operating a life-support system. If we want to place highly qualified individuals in the sea, we will have to make their environment comfortable and provide an effective place to work. Only then will we have graduated successfully from survival shelter, to habitat, to laboratory.

Life support for underwater habitats must be designed with adequate redundancy of critical elements and with built-in failure modes so that the whole system cannot fail at one time. Each life-support function must take into consideration the size and configuration of the habitat, crew size, duration of missions, nature of the work to be performed, and emergency reserves. It is possible to calculate the various parameters for a life-support system based on the average daily requirements of one individual. Table 6-1 shows the characteristics of a "standard man," defined as a male engaged in very light work without consideration of increased need for oxygen or increased output of carbon dioxide during a stressful situation. Although these data were assembled for designing small submersibles, they can serve as guidelines for the design of diving bells and undersea habitats.

Table 6-1. "Standard Man" for Life-Support System Design Computations

Item	*Quantity*	*Units*
Oxygen consumption	0.9	Ft^3/hr at 760 mm Hg
Respired air	18.	Ft^3/hr at 760 mm Hg
Drinking water	6	Pounds/day
Food, dry	1.4	Pounds/day
Respiration quotient	.85	Volume of CO_2 produced to O_2 consumed
CO_2 produced	.77	Ft^3/hr at 760 mm Hg
Water vapor produced	4	Lb/day
Urine	4	Lbs/day
Feces	0.4	Lb/day
Flatus	0.1	Ft^3/day
Heat output		
Sensible	250	Btu/hr
Latent	220	Btu/hr
Total	470	Btu/hr

Source: From Busby, R., 1976, *Manned Submersibles,* Office of the Oceanographer of the Navy, Alexandria, Va., p. 410.

BREATHING MEDIA

The breathing gas used in all habitats built thus far has been either air, nitrogen-oxygen, or helium-oxygen mixtures. Because most habitats have been used in shallow water, air has been the most common breathing gas.

Air is the most convenient and least expensive breathing gas and is considered to be safe to a depth of 50 feet (15.2 m) for saturation missions up to 7 days in length. It is suspected that air exposures at this depth exceeding this duration can cause respiratory problems due to the cumulative toxic effects of hyperbaric oxygen (Miller, 1979).

For depths between 50 feet (15.2 m) and 120 to 130 feet (36.6 to 39.6 m), the most suitable breathing gas is a normoxic mixture of nitrogen and oxygen. A common method is to have the aquanauts breathe down the habitat gas (air) until the oxygen partial pressure reaches the desired level. A flow meter is then activated to allow sufficient air to be admitted to the habitat to make up for the oxygen utilized by the aquanauts. Table 6-2 shows the nitrogen-oxygen levels required to achieve a normoxic breathing mixture at selected depths.

From the standpoint of decompression and nitrogen narcosis, saturation at a given depth using a normoxic mixture is equivalent to a greater depth than if air were used as the breathing gas. Table 6-3 shows the equivalent depths when using air and normoxic breathing mixtures of nitrogen and oxygen. A habitat located at a depth of 50 feet (15.2 m) filled

Table 6-2. Percentages of Oxygen and Inert Gases Required to Achieve Normoxic Breathing Gas Mixtures

Depth			*Oxygen*	*Nitrogen*	*Helium*
(ft)	*(m)*	*ATA*	*(%)*	*(%)*	*(%)*
Surface		1.0	21.0	78.0+	
50	15.2	2.5	8.4	91.6	
75	22.9	3.3	6.4	93.6	
100	30.5	4.0	5.2	94.8	
120	36.6	4.6	4.6	95.4	
150	45.7	5.5	3.8		96.2
175	53.4	6.3	3.3		96.7
200	61.0	7.0	3.0		97.0
225	68.6	7.8	2.7		97.3
250	76.2	8.6	2.4		97.6
275	83.8	9.3	2.2		97.8
300	91.5	10.1	2.1		97.9
328	100.0	10.9	1.9		98.1

Table 6-3. Equivalent depths for Air and Normoxic Breathing Gases

Air Depth		Air P_{O_2} ATA	Equivalent Normoxic Depth $P_{O_2} = 0.2095$	
Ft	m		Ft	m
0	0	0.79	0	0
5	1.5	0.94	3.9	1.2
10	3.0	1.09	7.9	2.4
15	4.6	1.24	11.8	3.6
20	6.1	1.39	15.8	4.8
25	7.6	1.55	19.7	6.0
30	9.1	1.70	23.7	7.2
35	10.7	1.85	27.6	8.4
40	12.2	2.00	31.6	9.6
45	13.7	2.15	35.5	10.8
50	15.2	2.30	39.5	12.0
55	16.8	2.46	43.4	13.2
60	18.3	2.61	47.4	14.4
65	19.8	2.76	51.3	15.6
70	21.3	2.91	55.3	16.8
75	22.9	3.06	59.2	18.0
80	24.4	3.21	63.2	19.3
85	25.9	3.37	67.1	20.4
90	27.4	3.52	71.1	21.7
95	29.0	3.70	75.0	22.9
100	30.5	3.82	79.0	24.1
105	32.3	3.97	82.9	25.3
110	33.5	4.12	87.9	26.8
115	35.1	4.28	90.8	27.7
120	36.6	4.43	94.8	28.9
125	38.1	4.58	98.7	30.1
130	39.6	4.73	102.7	31.3
135	41.2	4.88	106.6	32.5
140	42.7	5.03	110.6	33.7
145	44.2	5.18	114.5	34.9
150	45.7	5.34	118.5	36.1

Source: After Miller, J., ed., 1979, *NOAA Diving Manual: Diving for Science and Technology*, 2d ed., Govt. Printing Office, Washington, D.C.

with a normoxic breathing gas would have 8.4% oxygen and 91.6% nitrogen as shown in Table 6-2. This same habitat at a depth of 100 feet (30.5 m) would have a normoxic breathing mixture of 5.2% oxygen and 94.8% nitrogen. A normoxic mixture at 102.7 feet (31.3 m) exposes the aquanauts to the same amount of nitrogen as if they were saturated on air at a depth of 130 feet (39.6 m), as can be seen in Table 6-3.

Although there are large individual differences in susceptibility, most divers begin to show signs of nitrogen narcosis at a depth of about 150

feet (45.7 m) when breathing air. This is equivalent to about 120 feet (36.6 m) when breathing a normoxic mixture of nitrogen and oxygen (see Table 6-3). Therefore although the recommended maximum safe depth of 50 feet (15.2 m) for saturation using air is due to problems associated with oxygen toxicity, the maximum safe depth of 120 feet (36.6 m) for saturating on a normoxic mixture is due to the onset of nitrogen narcosis.

Customarily saturation dives at depths in excess of about 150 feet (45.7 m) have used helium as the inert gas in place of nitrogen, or a combination of oxygen, nitrogen, and helium. The use of three gases (trimix) is widespread in the field of commercial diving, and many combinations have been used at depths ranging from 150 feet (45.7 m) to over 2000 feet (610 m). Trimixes also have been used in several habitat programs, including Link's 1962 program, Sealab I and II, and Seatopia.

The principal advantage of helium is that it shows no narcotic effect over a wide range of depths. Helium has several disadvantages; for example, because its high thermal conductivity is six times that of nitrogen, body heat loss is significantly greater. Aquanauts require temperatures approaching 90°F (32.2°C) in a habitat in order to feel comfortable when the breathing gas is helium. Another disadvantage of helium is the well-known Donald Duck voice, which presents serious communication problems. There now are electronic helium unscramblers that convert the garbled helium speech to intelligible sounds. A third disadvantage of helium is that it has a propensity to leak into equipment, especially electronic equipment, and cause it to malfunction. Nevertheless the fundamental advantage of helium—the elimination of narcosis—far outweighs the disadvantages, all of which have been overcome through advances in technology.

In summary, air is the breathing gas of choice for depths from the surface to 50 feet (15.2 m), nitrogen-oxygen mixtures are safe and cost-effective to saturation depths between 50 feet (15.2 m) and 120 feet (36.6 m), and helium-oxygen mixtures or trimixes of helium, oxygen, and nitrogen are the choices beyond saturation depths of 120 feet (36.6 m).

CARBON DIOXIDE AND ODOR REMOVAL (SCRUBBERS)

Unless air with regular venting is to used exclusively, the design of any habitat must include a method for removing CO_2, odors, and trace contaminants. Even if air is to be used, some method of emergency control of CO_2 should be available.

The primary source of CO_2 in a habitat is the expired gas of the aquanauts. According to the U.S. Naval Material Command (1973), an average consumption of 1.0 standard cubic foot per hour (SCFH) of

oxygen per person will generate an average of 0.80 to 0.85 SCFH of carbon dioxide (depending on dietary considerations), an equivalent of 0.1 pound per man-hour. The sizing of a CO_2 removal system, also discussed in Penzias and Goodman (1973), can be calculated as follows: To derive the rate of carbon dioxide buildup, the Respiratory Quotient (RQ) is required, which is equal to the volume of carbon dioxide produced for each volume of oxygen consumed, or:

$$RQ = \frac{\text{Volume of } CO_2 \text{ Produced}}{\text{Volume of } O_2 \text{ Consumed}} = \frac{0.85}{1} = 0.85.$$

In a closed submersible, carbon dioxide will increase in accordance with:

$$\%CO_2 = 0.03 + \frac{(RQ) \text{ X } O_2 \text{ (Consumption Rate) X T}}{V/N}$$

where T = time in hours, V/N = floodable volume per person, RQ = respiratory quotient, and 0.03 = % of CO_2 in "clean" air.

The U.S. Navy recommends that 0.014 atmosphere partial pressure (1.5%) be the exposure limit of carbon dioxide, while 0.02 atmosphere (2%) indicates an emergency situation. The American Bureau of Shipping recommends a maximum of 1% for long-term exposure. The Marine Technology Society agrees with this maximum but notes that a maxi-

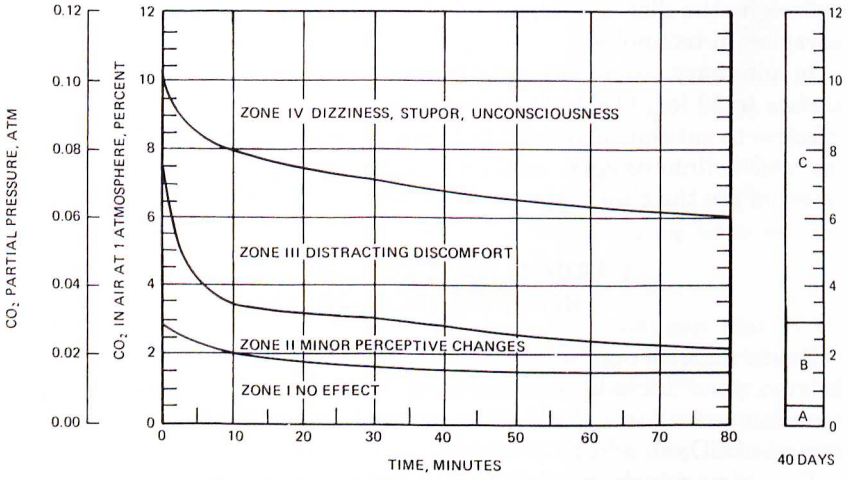


Figure 6-1. Relation of physiological effects to carbon dioxide concentration and exposure period. (*From J. Miller, ed., 1979, NOAA Diving Manual: Diving for Science and Technology, 2nd ed., Govt. Printing Office, Washington, D.C., p. 2-7.*)

mum CO_2 level of 0.5% should be the goal for 60- to 90-day missions (Busby, 1976).

Serious consequences of elevated levels of CO_2 are well documented and are illustrated clearly in Figure 6-1. The cumulative effects of long-term exposure are of particular importance for undersea habitats where exposure of many days or weeks is the rule rather than the exception.

More than thirty methods have been proposed for the removal of CO_2 from the environment. Most widely used CO_2 absorbents for undersea habitats have been barium hydroxide (Baralyme), soda lime (Sodasorb), or lithium hydroxide, all nonregenerative chemical agents. Baralyme is a weak alkali, and lithium hydroxide is a stronger alkali. The characteristics of these three agents are shown in Table 6-4.

Many factors influence performance of CO_2 absorbents, including space, temperature, humidity, transfer systems from the surface, weight, and canister design. The following summary of these factors was made in the report of the Johnson Sea-Link (1973, pp.57-58):

> The rate at which carbon dioxide is absorbed in absorbents is influenced by temperature, and is considerably lower at 40°F (4.4°C) than at 70°F (21.1°C). In some scrubbers, sized for adequate performance at 70°F, absorbing capacity at 40°F may be as little as 1/3 that at 70°F. This effect is strongly dependent upon the canister design and the rate of carbon dioxide absorption, being most evident in absorbers working at peak flow rates, and least evident in oversized scrubbers and those used intermittently.
>
> It appears desirable to provide external insulation and heating of scrubbers for use in cold water as a means of minimizing size and assuring that the design absorbent capacity can be obtained. This also is advisable as a

Table 6-4. Characteristics of Three Carbon Dioxide Absorbents

Characteristic	*Absorbent*		
	Barium Hydroxide	*Lithium Hydroxide*	*Soda Lime*
Absorbent density, lb/ft³	65.4	28.0	55.4
Theoretical CO_2 absorption, lb CO_2/lb	0.39	0.92	0.49
Theoretical water generated, lb/lb CO_2	0.41	0.41	0.41
Theoretical heat of absorption, BTU/lb CO_2	670[a]	875[a]	670[b]
Useful CO_2 absorption, lb CO_2/lb (based on 50 percent efficiency)	0.195	0.46	0.245
Absorbent weight, lb per diver hr (0.71 lb CO_2)	3.65	1.55	2.90
Absorbent volume, ft³ per diver hr	0.0558	0.0552	0.0533

Source: After Busby, R., *Manned Submersibles,* Office of the Oceanographer of the Navy, Alexandria, Va., p.421.

[a] Based on calcium hydroxide reaction only.

[b] Based on generating gaseous H_20.

means of avoiding moisture condensation. A possible alternative is to design for about three times the absorbent capacity needed at 70°F (21.1°C).

The efficiency of CO_2 absorbents also is influenced by relative humidity. The absorbing capacity quoted for Baralyme and soda lime, for example, is obtained only when relative humidity is above 70%. In habitats, breathing humidity usually would be well above 70% unless the scrubber system is preceded by a dehumidifier.

Under conditions of high gas humidity and low scrubber surface temperature, water may condense on canister walls or in the absorbent. This situation is undesirable because wet absorbent is inactive and impervious to air flow, reducing absorptive capacity and increasing pressure drop through the canister. Scrubbers for use in cold water can be designed to minimize moisture condensation by incorporating thermal insulation or heating of the canister. "None of the absorbent-bed configurations now in use seem to have advantages that make them universally applicable. Principal design requirements are to provide an adequate amount of absorbent, very uniform distribution of gas flow through the absorbent bed, and sufficient time for the absorption reactions to occur" (Report of the Johnson Sea-Link, 1973, p. 58).

The basic mechanism of a CO_2 scrubber is simple. A fan draws air from the habitat atmosphere, forces it through the chemical agent where CO_2 is removed, and subsequently redistributes it throughout the habitat. A scrubber also may have the capability to remove odors and trace contaminants, the most common methods being through absorption and adsorption either in activated carbon or activated alumina impregnated with potassium permanganate. The latter handles odor-causing and trace contaminants, including esters, ketones (from paints and solvents), oxides, and phenols (Penzias and Goodman, 1973). The odor-removing agent may be mixed with the CO_2 absorbent or held in a separate bed in the air ducting. Great care must be taken when constructing a habitat not to use paints, adhesives, plastics, or other synthetic material that could produce toxic off-gasing or cause a dangerous concentration of toxic or combustible concentrations of substances. Because the mission duration of habitat programs usually is considerably longer than the average submersible dive, extra care must be taken with respect to selection of materials because some may be safe for use in submersibles but not for long exposures in a habitat.

Scrubber systems for habitats have varied widely in both size and configuration. Sealab II used a manifold containing twelve 6.2-pound (2.8 kg) canisters of lithium hydroxide. This system maintained the CO_2 level at less than 0.02% for 24 hours or longer (Pauli and Clapper, 1967). The level would then rise rapidly to about 0.25% within about 36 hours after

the canisters were changed, which usually was before CO_2 levels reached 0.3%. After changing, carbon dioxide concentration fell precipitously, often below 0.01% in a few hours.

Designers of Tektite chose to use a single scrubber for the entire habitat. Because the habitat was very large and was divided into four separate rooms, a complex ducting system and a large electrical demand were required. In addition, Baralyme was used, which meant frequent changes were required. The result was that 50 pounds (22.7 kg) of Baralyme had to be changed every 8 hours, requiring 25% of the habitat engineer's time (Fig. 6-2). Further, about half of the usable storage space in the habitat was occupied with Baralyme canisters.

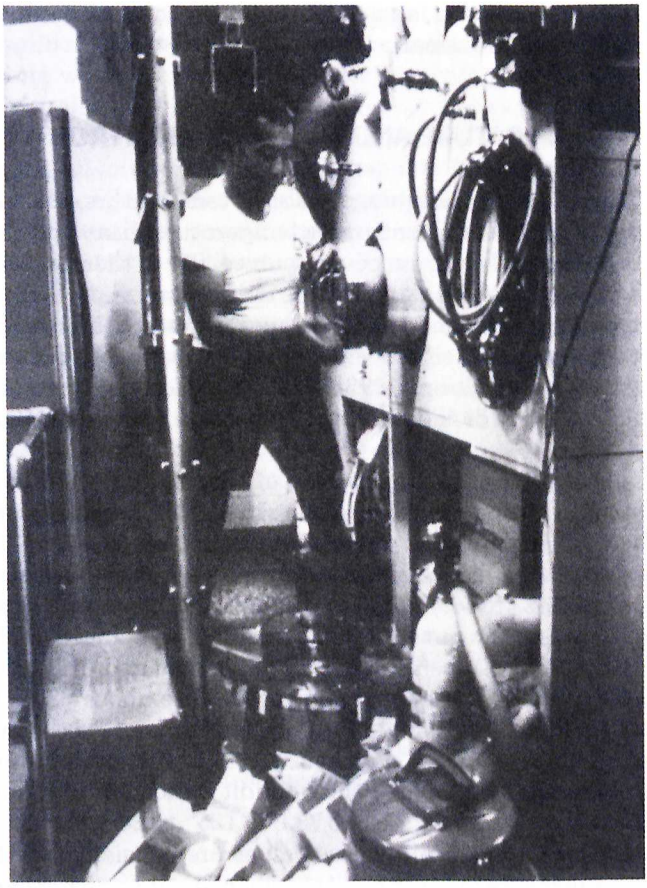


Figure 6-2. Tektite II habitat engineer wallowing in Baralyme containers. (*courtesy of General Electric Company.*)

A significant amount of the aquanauts' time was spent in dry transfer of Baralyme from the surface up through the entrance trunk (Fig. 6-2). By contrast, the La Chalupa habitat, whose area was only slightly smaller than Tektite, used a separate explosion-proof fan in each living compartment that pulled breathing gas through a standard navy lithium hydroxide canister. The canister (the grey cylinder under the sink shown in Fig. 4-44), fitted with a charcoal filter, was replaced once every 24 hours. Cousteau used a cryogenic CO_2 scrubbing system in Conshelf III. Although the system generally was successful, a number of mechanical problems were encountered.

As the most critical element in a habitat life-support system, the CO_2 scrubber must be selected with great care and take into account all aspects of the habitat operation. Failure to do so will result not only in potentially life-threatening situations but also in chronic deleterious effects on aquanaut performance.

TEMPERATURE AND HUMIDITY CONTROL

Factors to consider in designing a habitat temperature and humidity control system include ambient water temperature, heat and humidity produced by the crew, heat from power sources, use of thermal insulation and whether it is located inside or outside the habitat, vapor sources such as cooking and showers, and the CO_2 removal system. Not only does a CO_2 scrubber generate a significant amount of heat, but according to Canty, Lanphear, and Morin (1972), About 1 ft^3 of water vapor is produced per ft^3 of carbon dioxide removed by lithium hydroxide, Baralyme, or Soda Lime.

A good illustration of the interaction of these factors is found when comparing two missions conducted during the 1972 Chernomor program. During the first mission, the outside water temperature was 69.8° to 73.4°F (21° to 23°C), while during the second mission the water temperature dropped to 39.2° to 46.4°F (4° to 8°C). When the water temperature was reduced, moisture removal from the habitat was improved because the heating system was operating more of the time and dried the circulated air effectively. If the water temperature rose above 68°F (20°C), however, this method of dehumidifying was ineffective, and the humidity commonly reached 94 to 97% (Grinevich, 1975). The Soviet aquanauts performed more effectively when the humidity and temperature inside the habitat were 80 to 85% and 77° to 78.8°F (25° to 26°C), respectively, at a depth of 49.2 feet (15 m). These values are consistent with those preferred by aquanauts in other habitats when an air or nitrogen-oxygen atmosphere is used.

Because one of the primary objectives of employing a seafloor habitat is to allow aquanauts to spend long periods of time in the water, the importance of having an adequate heating system cannot be overemphasized. Unless specially heated suits are used, the aquanaut eventually will get too cold to operate effectively even in tropical waters. Further, because repetitive dives are the rule and not the exception, it is essential that the aquanaut warm up between dives. Heat loss is serious not only from a physiological standpoint, but it also will seriously affect the aquanaut's ability to perform effectively.

A prime example of the debilitating effect of cold on aquanaut performance was experienced during a dive in the Aegir habitat between June 1 and 5, 1970. The dive was made off the coast of Oahu in the Hawaiian Islands at a depth of 516 feet (157 m) in water temperatures of 67° to 70°F (19.4° to 21.1°C). According to Pegg (1971), once the habitat was on the seafloor, the interior temperature dropped nearly to that of the surrounding water and remained so despite deployment of heaters. This problem coupled with the fact that the control system was unable to maintain relative humidity below 80% created an uncomfortable and highly stressful environment. The aquanauts' behavior clearly was that of individuals under stress. They were continually cold, even when sleeping under conventional covers, and frequently awoke shivering. According to Pegg (p. 1261), "The most significant medical aspect of this dive was the effect of the low habitat temperature on the divers. Their outside diving time, based upon their own estimates, was less than one-third of what could have been spent in these waters had they been able to adequately re-warm." Because of the cold and mechanical problems, the six aquanauts were able to spend only a total of 22 hours in the water during the 5-day mission, an average of 44 minutes per day per aquanaut in the water.

Although the problems in the Aegir habitat were accentuated because of the helium environment, they illustrate the serious consequences of an inadequate heating system. As pointed out in a University of New Hampshire report (1972, p. 180):

> Temperature control will probably vary from conditions where sensible heat will have to be removed to maintain a comfort level (water temperature, 70-75°F) [21.-23.9°C] to cases where need will exist to supply heat (water temperature, 35-55°F) [1.7-12.8°C]. If the habitat is to be adapted for both extremes, a heat pump system or equivalent will have to be given consideration whereby the environmental control system can provide heating as well as cooling.

A combination of heated floors and heated air also can provide a comfortable environment. Some environmental-control systems circulate

gas or air from the vehicle cabin or chamber through a carbon dioxide removal system. The temperature of the gas then can be reduced using a heat exchanger for water condensation and humidity control, and subsequently raised again to the appropriate temperature. Although it is difficult to generalize about temperature-humidity control systems for habitats, the technology has long been available; there is no excuse for an inadequate system.

FOOD AND WATER MANAGEMENT

When humans find themselves in hazardous isolated environments, food storage, preparation, and consumption seem to assume importance far beyond that experienced in everyday life. As a consequence, the psychological cohesiveness and performance of an underseas crew may be related directly to the food management program.

The first step in food management is menu selection. This should be done well in advance of a mission in order to facilitate ordering, loading, and storage aboard the habitat. Meals must be varied and nutritious and provide each crew member with approximately 2800 calories per day of palatable food. A mixture of frozen, dehydrated, and thermostabilized foods helps not only to break up the monotony but also facilitates food storage. In Conshelf III, although most of the meals were of the frozen TV type, a variety of canned juices were provided and stored outside the habitat in a wire pantry where the 50°F (10°C) water kept them at a good drinking temperature. In Sealab II, most of the food was canned and of the heat-and-eat variety, with occasional meals sent down from the surface to break the monotony.

Food delivery systems for habitats have been quite varied and often reflected considerable ingenuity. Aquanauts living in the Soviet habitat Sprut (Fig. 9-27) received food through a tube from the surface in a sort of slurry form. While this does not sound particularly appetizing, it does seem efficient. In the more sophisticated Chernomor habitat, Soviet aquanauts were delivered meals three times a day in containers from the surface and were prepared by a special chef during some of the missions. The meals were balanced in diet and averaged about 4500 to 5000 calories per day, significantly higher than for American aquanauts.

In many of the smaller habitat programs, meals also were prepared on the surface and delivered daily to the seafloor. For example, the Czech/Cuban Caribe I project (Fig. 9-6) and Conshelf I followed this practice. In the latter instance, food was sent down in a pressure cooker after being prepared by the cook of the support ship *Espadon.* An electric stove was available in Conshelf I to rewarm food or to cook it should meal delivery be interrupted.

In Tektite, Sealab, La Chalupa, and Hydrolab, food was stored on board prior to the mission in an effort to minimize the need for support divers' having to replenish supplies. For these programs, food was provided in all forms, including frozen, freeze-dried, canned, and fresh. No amount of planning seemed to avoid the need for additional food, either because of running out or because of special requests of the aquanauts, which at times created antagonism between aquanauts and support crews. The support crews occasionally felt the aquanauts were being pampered and unreasonable in their demands, which sometimes created a lot of extra work for the support crew.

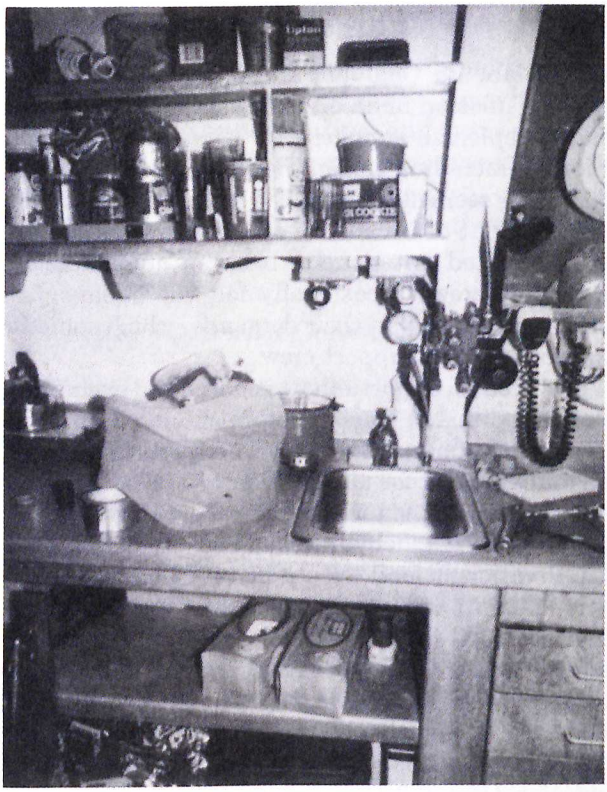
Tektite II provided an opportunity to collect and evaluate data on food preferences and food management over an extended time (Smith, et al., 1971). The study was conducted by NASA experts interested in parallels between food management for undersea crews and space crews. A variety of foods were provided to the ten five-person crews over the seven-month program, including frozen, dehydrated, and thermostabilized. The study concluded that sufficient food should be provided for four meals a day. The types should be mixed—that is, some frozen, some canned, and so forth. Freeze-dried food is a particularly attractive packaging style for habitats because it does not require refrigeration, it comes in a variety of food types, and it is easy to prepare. If possible, all food should be loaded prior to the start of a mission and marked carefully as to contents.

Habitat facilities for preparing hot food have included a simple hot plate in Hydrolab (Fig. 6-3*A*), a special electric stove in Sealab II, a standard commercial oven-stove in Tektite (Fig. 6-3*B*), the well-equipped galley of Helgoland (Fig. 6-3*C*), and the preferred microwave oven used in La Chalupa (Fig. 4-43).

Regardless of the type of system, all cooking should be done in closed vessels to reduce the amount of water vapor, and hence humidity, added to the atmosphere. Frying introduces excessive hydrocarbons into the atmosphere and should not be allowed. Boiling also is discouraged because it adds to an already existing problem of high humidity. An interesting feature of life in a habitat is that water boils at substantially higher temperatures as pressure increases. Table 6-5 shows the boiling point of freshwater as a function of atmospheric pressure. Comparable data for soup and coffee are not available.

The water supply system of a habitat carries freshwater from the supply reservoir to the sinks and/or shower. When water is stored on board, the low-pressure air system can be used to pressurize the water tanks, thus eliminating the use of a water pump.

Freshwater consumption in underwater habitats depends for the most part on the external water temperature and the source of the water supply. Where water is supplied from the surface and is virtually unlimited,



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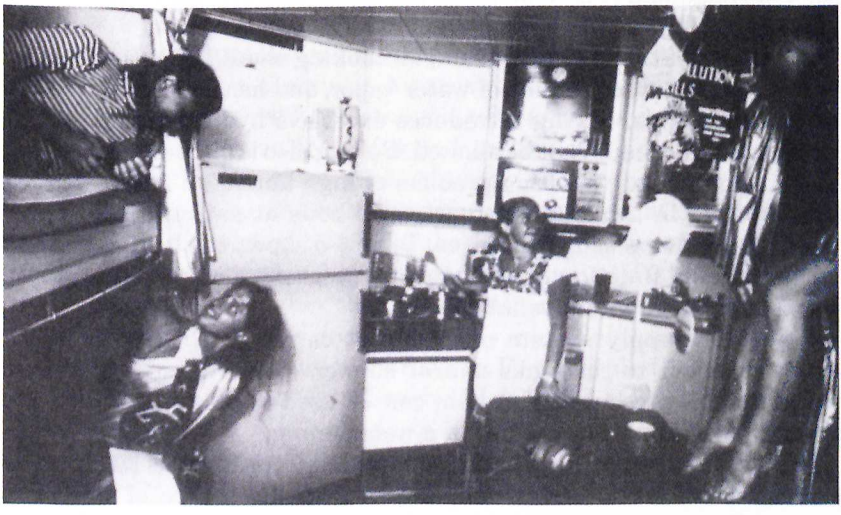

B



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Figure 6-3. Cooking facilities for three habitats. *A:* Hydrolab (*courtesy of National Oceanic and Atmospheric Administration*); *B:* Tektite (*courtesy of General Electric Company*); *C:* Helgoland (*courtesy Society for Nuclear Research in Ship-Building and Navigation, Bonn, Germany*).

daily consumption can approach 70 gallons (265 l) per person. On the other hand, when water is stored aboard the habitat, consumption must be reduced drastically. For example, during Conshelf III where the outside temperature of the water was 50°F (10°C), the average water consumption was 20 (75.7 l) gallons per person per day. This was the same rate of use as in La Chalupa where the external water temperature was about 78°F (25.6°C). La Chalupa had a storage capacity of 1500 gallons (5678 l), found to be ample for a crew of five for 2 weeks.

Table 6-5. Boiling Point of Freshwater as a Function of Atmospheric Pressure

	Depth		Boiling Point	
ATA	(ft)	(m)	(°C)	(°F)
1	0	0	100.0	212.0
2	33	10.0	121.5	250.7
3	66	20.1	134.0	273.2
4	99	30.2	144.1	291.4
5	132	40.2	152.3	306.1
6	165	50.3	159.5	319.1
7	198	60.4	165.5	329.9
8	231	70.4	171.0	339.8
9	264	80.5	175.9	348.6
10	297	90.5	180.4	356.7

Storage of water in a habitat usually presents no problems. It may be stored externally as with Conshelf III and Helgoland where the water bags were used as ballast, with freshwater being replaced with seawater during the mission to compensate for changes in buoyancy. Other storage areas include tanks on the deck of the habitat or in a buoy on the surface as was used for Hydrolab. An interesting feature of the La Chalupa habitat was the use of water beds. Not only were they comfortable to sleep on, but each bed contained over 70 gallons (265 l) of fresh water for emergency use. The water beds were rinsed with chlorine prior to use, then filled with chlorinated water, and subsequently protected from light. Water stored under such conditions will remain potable for long periods of time.

WASTE MANAGEMENT

The waste management system for an undersea habitat must provide for collection, processing, and disposal of biological waste, perishable and moist waste, and nonperishable hard waste. It also must be designed to function when the habitat is under pressure, as well as when it is on the seafloor under ambient conditions.

The disposal of garbage frequently has been considered only as an afterthought. In Sealab and Tektite, as with most other habitat programs, garbage was carried away daily by surface-support divers after it was placed in transfer pots by the aquanauts (Fig. 5-23). In the Tektite program the amount of garbage produced was enormous. One of the chief reasons was that more than 50 quart containers (47.3 l) of Baralyme were required daily to keep the scrubber system functioning properly (Fig. 6-2). These containers, in addition to normal food wrappers, cans, and bottles, produced about 30 gallons of trash per day, which was placed in a 400-pound (181 kg) transfer pot and hauled to the surface (Fig. 5-23). Garbage and trash disposal was handled in the La Chalupa habitat by

installing a household garbage compactor. Two weeks of garbage were compacted into about three bags, which could be placed individually in a large plastic trash bag and sent to the surface.

A waste management system also must provide drainage for the sink and shower. Hot freshwater showers are very important in any undersea habitat, and the longer the mission, the more important they become. Care must be taken, however, to isolate the shower from the air-conditioned or heated compartments of the habitat, if at all possible, to minimize the increase in humidity. In single-room habitats like Hydrolab or Edalhab (Fig. 6-4), the shower was located in the entrance trunk, which minimizes the problem. In Tektite, La Chalupa, and Aegir, the shower was separated from the main living quarters. Disposal of shower water is accomplished most readily when the shower is in the wet room, as in La Chalupa (Fig 4-42) and Aegir. This arrangement also facilitates washing of equipment and wet suits and cleaning of specimens.

Sinks and wash basins must be designed to be usable at depth. They can function in several ways depending on configuration of the habitat. If the habitat is to be used for decompression and/or is designed to be pressurized while on the seafloor, the drain system must be pressurized. Normally, pressurization is accomplished by placing a small holding tank below each sink to receive water (Fig. 4-44). An air valve between the drain and holding tank permits the tank to be pressurized to about 10 to 15 psi

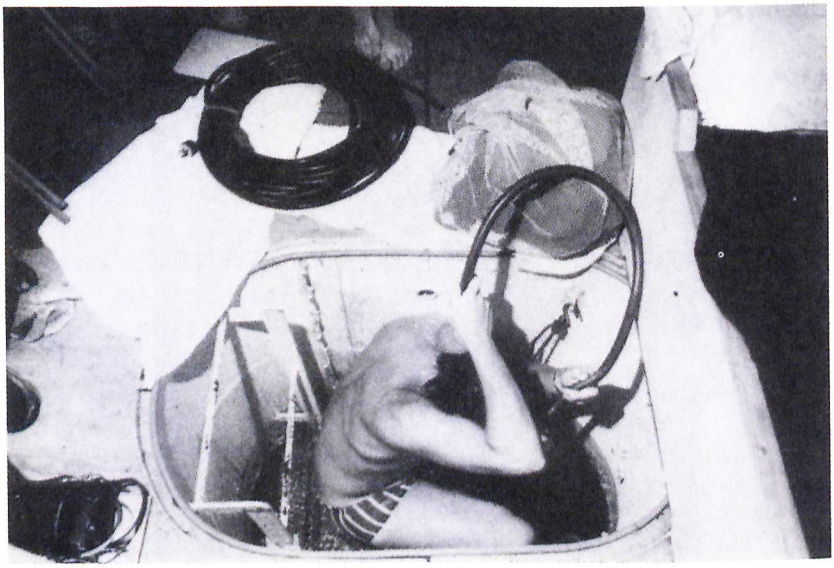


Figure 6-4. Aquanaut showering in Edalhab entrance trunk. (*courtesy of William High, National Oceanic and Atmospheric Administration, Seattle, Washington.*)

(0.7 to 1.0 kg cm^2) over bottom pressure. The waste water then is blown out of the tank (Fig. 6-5).

Toilets for undersea habitats have ranged from disposable plastic bags to rather elaborate flush toilets and chemical units. The system chosen depends on the configuration of the habitat, anticipated duration of the mission, makeup of the crew with associated considerations for privacy, depth of the operations, and in some cases the prevailing currents in the water surrounding the habitat. This last factor was of concern to aquanauts using the Hydrolab habitat. The absence of a toilet inside required careful planning when using the surrounding environmental facilities. By contrast, in Sealab II and Tektite, a standard marine toilet was used with a saltwater flushing system and overboard discharge connections.

In La Chalupa several toilets were tried before one was found acceptable to both the aquanauts and support divers, including one that required the holding tank to be transported periodically to the surface. As it turned out, the reduction in pressure on the way to the surface caused the holding tank to explode, with disastrous consequences. Other experiments finally led to the fabrication of a special fiberglass toilet (Fig. 6-6) connected to a 4-inch (10.2 cm) pipe, which in turn was joined to several lengths of PVC tubing. The pipes were routed to an appropriate location nearby. After each use, seawater was dumped from a bucket into the bowl to flush it. This system was quite simple and effective when compared to the sophisticated stainless steel toilet used in the Helgoland habitat (Fig. 6-7).



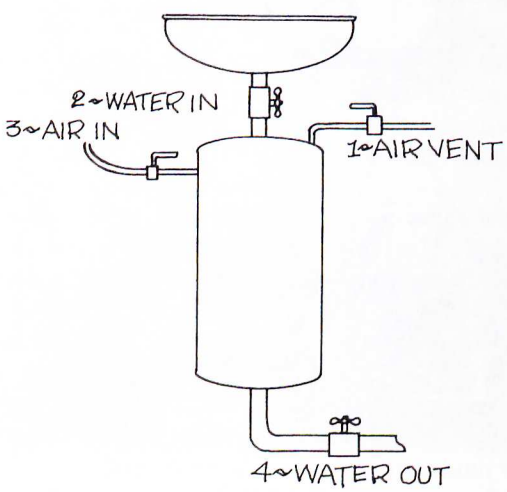


Figure 6-5. Diagram of sink discharge system for La Chalupa.

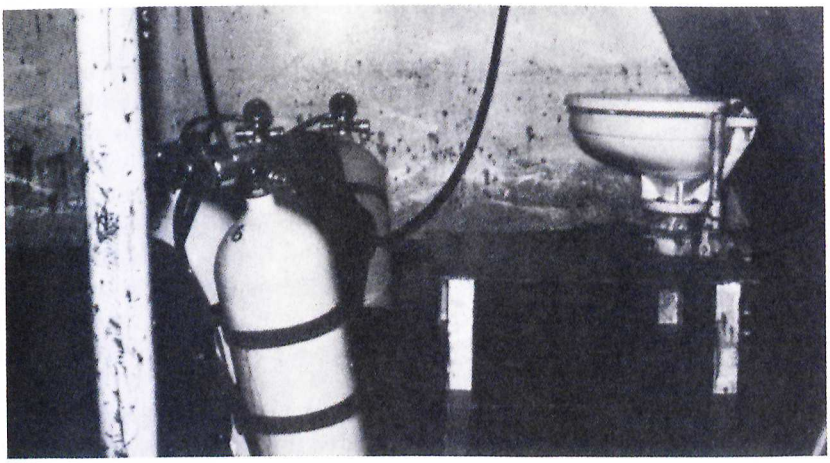


Figure 6-6. Toilet used in La Chalupa. (*courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida.*)

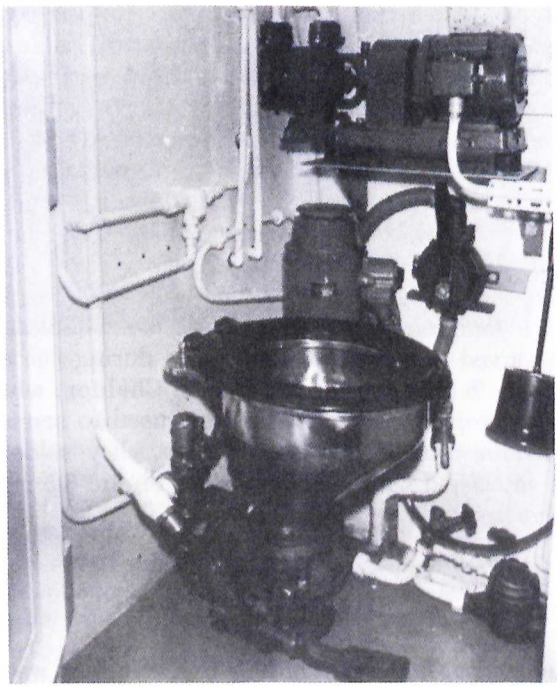


Figure 6-7. Toilet used in Helgoland habitat. (*courtesy of Society for Nuclear Research in Ship-Building and Navigation, Bonn, Germany.*)

SLEEPING ACCOMMODATIONS

Sleeping accommodations in habitats traditionally have been spartan; they have ranged from a blanket on a steel deck to cots, to air mattresses, to regular mattresses, to water beds. The selection of bedding is restricted because of the possibility of combustion in those habitats where decompression was planned and/or elevated oxygen levels were to be encountered.

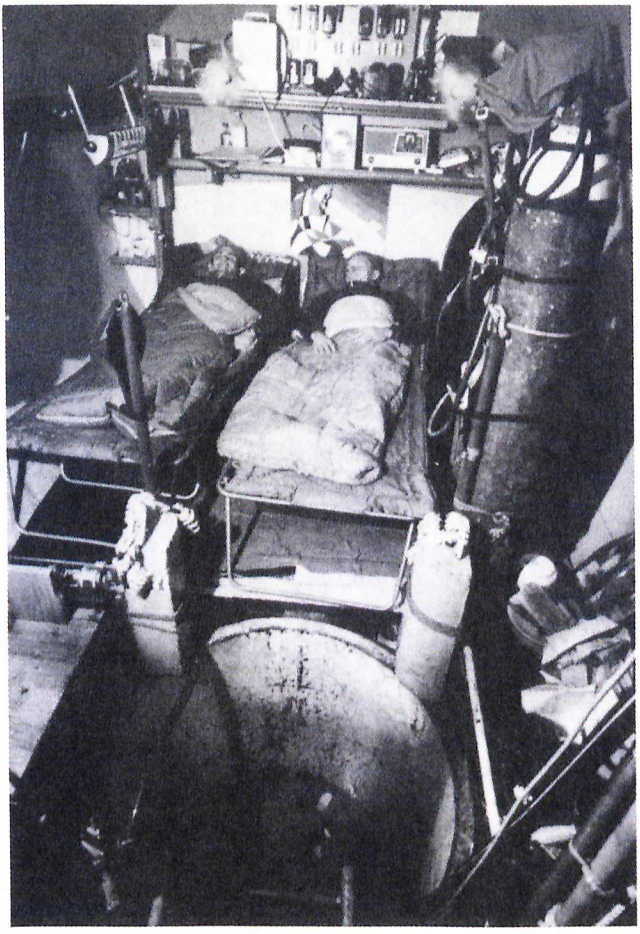
The first U.S. habitat to use a regular mattress was Tektite I. This use was safe because the breathing mixture in the habitat contained only about 9% oxygen, which would not support combustion. Further, Tektite was not a pressure vessel; thus decompression could not be carried out in the habitat. Even with this margin of safety, the mattresses were covered with fire-retardant material.

The use of water beds in undersea habitats was first suggested by the author (Koblick). They offer a number of advantages where weight is not a problem. In addition to being comfortable and nonflammable, they can store large quantities of freshwater. With coverings removed, a water bed also can assume the role of a heat sink in the event the habitat becomes uncomfortably warm. Experience with La Chalupa where water beds were first used revealed that they must be strapped down while the habitat is under tow. Even a relatively calm sea can produce waves in the water bed to the point where the bed can throw itself out of the bunk frame onto the floor. This happened during an early La Chalupa mission, spilling 500 gallons (1892 l) of water over the floor and equipment. During a tow in a heavy sea at the end of a mission, we found we had to be strapped in or be thrown to the floor by the high sea state in the water beds. More recent water beds incorporate a foam with the water, which keeps the water from forming breaking waves.

Other than beds, sleeping accommodations vary widely. In some habitats, privacy is at a premium. These are the one-room habitats or those in which bunks served as work areas or tables during the day. In other habitats, notably Tektite, Sealab II, and La Chalupa, where there was more than one compartment, curtains were used to screen the bunks. Although curtains seemed like a good idea, they seldom were used because they interfered with air circulation. Figure 6-8 shows sleeping quarters of five habitats.

HABITABILITY

Webster defines *habitable* as "suitable to live in." As we have learned, most underwater habitats were survival shelters but were not really suitable to live in and from a human engineering standpoint, were poorly



A

Figure 6-8. Sleeping accommodations in five habitats. *A:* Conshelf I, Diogenes (*courtesy of The Cousteau Society, Inc., 930 West 21st Street, Norfolk, VA 23517, a membership-supported environmental organization.*); *B:* Chernomor (*from M. Rostarchuk, 1969, Five Days Under the Sea, Sputnik (USSR), May, p. 89*); *C:* Hydrolab (*courtesy of William High, National Oceanic and Atmospheric Administration, Seattle, Washington*); *D:* La Chalupa (*courtesy of Marine Resources Development Foundation, Fort Lauderdale, Florida*); *E:* Aegir (*courtesy of William S. Busch, National Oceanic and Atmospheric Administration*).

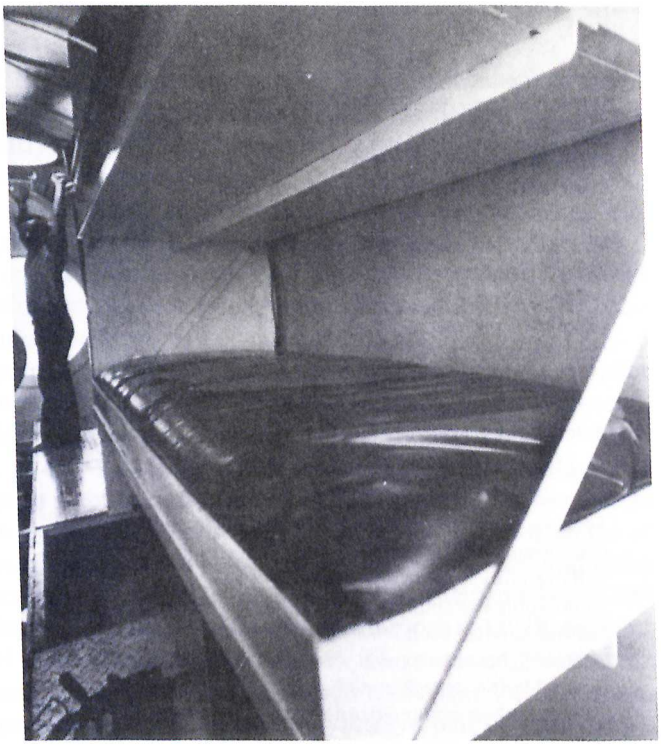


B



C

Figure 6-8. *(continued).*



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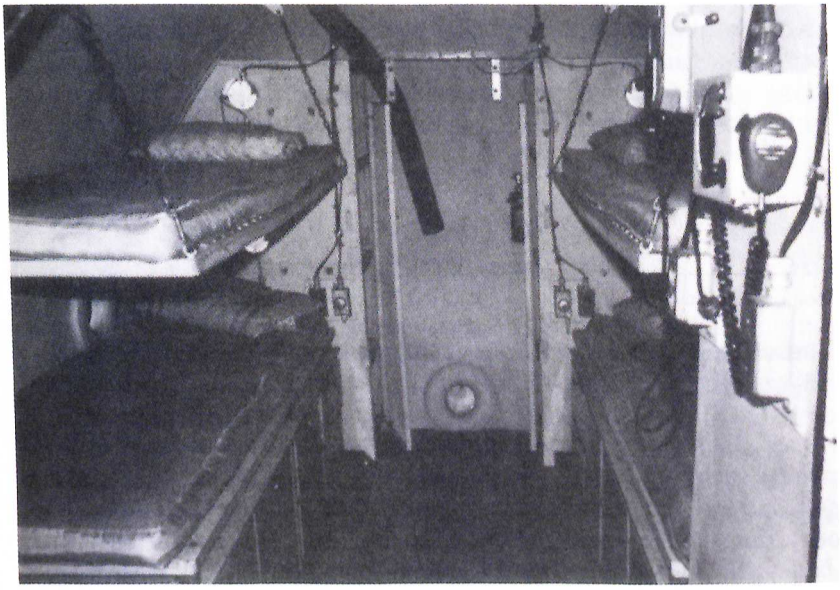

E

Table 6-6. Desirable Features for an Undersea Habitat

Separate wet room
Large entry trunk
Wet suit rack
Hot shower
Air hoses and emergency breathing systems
Scuba charging system
Wet lab bench
Specimen freezer
Clothes dryer
Diving equipment storage
General features
Hemispherical windows
Temperature and humidity control
Separate chambers for living and working
On-bottom and surface decompression capability
Suitable entry height off bottom
Submersible decompression chamber for emergency escape
External survival shelter
External lights at trunk and viewports
External bottle storage and charging
Habitat-to-diver communication
Adjustable legs
Mobility
External or protected internal chemical hood
Living room
Microwave oven
Food freezer and refrigerator
Water heater
Toilet
Individual desk and storage
Dry lab bench
Compactor
Tapes and radio

Source: After University of New Hampshire, 1972, *Manned Underwater Platforms,* Technical Report No. 111, Contract No. NG 35-72, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., p.29.
Note: Overall size about 8′ × 38′.

designed. In many instances, slight changes in design could have avoided problems such as congestion in the entrance trunk, hatches that were too small, and inefficient storage space. Lack of a functional layout has cost money, time, and in some cases, almost cost lives. It is not our intention to lay out the ideal habitat but rather to review some of the features of a comfortable seafloor house and identify some problems. Key concepts are

simplicity, functionality, and comfort. An aquanaut who is constantly wet, cold, and miserable for days at a time cannot be expected to perform efficiently and produce high-quality scientific results.

Small annoyances overlooked in a normal working environment become major problems when living under stressful conditions in close quarters. A major source of irritation in the Sealab II program was the lack of a little cubby hole in which to keep one's personal belongings. Under conditions of stress, these preferences become interpersonal issues all out of proportion to their normal importance.

Layout of work and living space has received much attention in the past and is well documented. Exhaustive studies have been made relating to physical anthropometry, design of work areas, layout of displays and controls, and creature comforts that can be used directly in the design of undersea habitats and laboratories. A good reference for these subjects is Van Cott and Kinkade (1972). NASA has spent millions on design and layout of space capsules; some of the findings are applicable directly to undersea habitats (Anon., 1971; and Parker and West, 1973). A report published by the University of New Hampshire (1972) summarizes features found to be desirable in a habitat. The data are presented in Table 6-6.

Recognizing that a certain amount of space sharing among occupants, equipment, and safety features always will be necessary, examples of mission-related features that should be included in future seafloor laboratories are work areas where live and wet specimens can be brought easily into the habitat for sorting and identification; dry areas for microscopes and similar equipment; specially lighted areas for specimen analysis; real-time readouts of local oceanographic data such as currents, temperature, visibility, and salinity; and perhaps a computer terminal to assist in data analysis. Many of these features were included in the La Chalupa habitat.

COMMUNICATION AND LIGHTING

Habitat communication systems have ranged from an airtight bucket with notes in it to sophisticated radio and TV systems. Good communication between the habitat and the surface usually can be achieved through an umbilical using high-quality commercially available systems. If the habitat is some distance from shore, such as during the La Chalupa program where the distance was 10 miles (16.1 km), a radio link also must be used.

Communication becomes more complicated if helium is used as a breathing mixture in the habitat. This difficulty is a result of changes in

the normal frequencies of the vocal tract, which shifts them upward due to the increased velocity of sound in helium-oxygen gas mixtures. Intelligibility decreases as the percentage of helium in the breathing gas increases, and speech becomes almost completely unintelligible in mixtures containing 90% or more of helium (Hollien, Thompson, and Cannon, 1971). While the Donald Duck voice is humorous as a novelty, it is a serious and sometimes dangerous problem in undersea programs. Fortunately, advances in technology have resulted in the development of helium unscramblers with the capability to alter the helium voice input electronically such that a much higher level of speech intelligibility is produced (Shilling, Werts, and Shandelmeier, 1976). Prior to the availability of unscramblers, aquanauts found it necessary to write notes or use devices such as the electrowriter, a device incorporating a writing pen (or stylus) on each end of a wire such that when an individual writes with one pen, the slave pen at the other end of the wire duplicates the message. The electrowriter was used in several early habitat programs such as Sealab II and Conshelf III where helium was used as the breathing gas.

Even with the availability of unscramblers, there is no alleviation of the problems of face-to-face communication in the habitat unless it is through an unscrambler. While there is an adaptation process, which includes speaking slowly, lowering the voice, and avoiding words known to be troublesome, everyday conversation can be a continuous source of frustration.

Many communication systems also have included the use of closed-circuit television. Excellent systems are commercially available, and habitat designers in the future should have a wide range of systems from which to choose, including black and white, color, low light level, and a large variety of hand-held or head-mounted systems for use in the water. Based on past experience, special attention when selecting TV or any other electronic equipment must be given to the sealing (potting) of components. Helium has the propensity to penetrate seals that are impervious to other gases such as nitrogen. In Sealab II, the only solution to this problem was to place the TV cameras facing inward at the ports in the water outside the habitat.

While habitat lighting should be planned in accordance with standard illuminating engineering practices, some features peculiar to a pressure environment must be considered. For example, although standard incandescent bulbs of low wattage can be used at depths to about 200 feet (61 m), fixtures should be explosion proofed so that in the event they are broken, they will not implode and shower the habitat with glass shards. The selection of fluorescent or heat lights must be made with care since breaking of these lights can release a gas capable of contaminating the habitat atmosphere. Thus extra care must be given to providing a suita-

ble encasement. Lights should be checked prior to installation in a hyperbaric chamber to a depth in excess of the anticipated exposure depth to confirm they are safe to use.

The interior of a habitat should be well illuminated for general moving around, as well as furnishing specific area lighting for work places. Locating work areas near ports promotes effective use of light and also permits the aquanaut to make external observations while working. Special lighting may be needed to allow observations to be made at night and recorded without reflections interfering with outside viewing.

Exterior lighting is not a luxury; it is important from the standpoint of scientific observations and serves as a beacon for aquanauts making night dives. In addition, external lights provide aquanauts with hours of entertainment once the day's chores are finished. It is at night that the feeling of being in the sea is most compelling. Turning on outside lights and catching the passing scene in almost stop action is an unforgettable experience. Exterior lights can be mounted on the habitat and also on an extension cord. A 1000-watt quartz-iodide light has been found quite satisfactory for this purpose. These and other halide lights have a fairly long life (300 to 600 hours) if operated properly and under good conditions. Care must be taken, though, to avoid lifting them out of the water while still turned on to prevent overheating and breaking.

An interesting use of external lights was made during some of the La Chalupa missions. The lights were turned on until fish of all sizes were attracted to the habitat. The external lights were then turned off and the wet room lights turned on. The fish would swarm to the wet room entrance and literally leap out of the water to reach the light located in the air space in the wet room. An aquanaut would scoop up the fish and throw them to a waiting friend who would toss them into the microwave oven for a 5-second kill. The fish was then cleaned, cooked, and served for dinner.

DIVING FACILITIES AND PROCEDURES

Diving facilities should include an area for suiting up, for storage of diving suits and scuba equipment, umbilical hose storage, air tank charging, and easy entrance and exit of the habitat.

A common criticism of saturation diving as practiced in seafloor habitats is that the aquanauts spend less time in the water than one would expect. To a large extent, the criticism is justified. Some explanations offered in response to this criticism are the long hours of maintenance required, failure of equipment, interference from topside, cold, and fatigue. A reason often overlooked is the time consumed by filling air

tanks. Some habitats have been designed such that it is necessary for scuba cylinders to be sent to the surface and filled by support divers. Although this is convenient for the aquanauts, it is time-consuming for support divers, requires continual advanced planning, and is dependent entirely on weather conditions at the surface. Hydrolab had an air filling station outside the habitat, a significant improvement in that aquanauts could fill scuba cylinders independent of the surface. Even this method required the aquanaut to leave the habitat, however, and in most instances was regarded as a chore.

The Tektite habitat scuba-charging equipment consisted of two high-pressure compressors on the support barge, a high-pressure umbilical from the compressors to the habitat, three 270-standard-cubic-foot (3.6 m^3) accumulator tanks mounted external to the habitat, and associated valves and charging lines. A hookah system drew air from the scuba-charging equipment through a stepdown regulator. The scuba-charging and hookah units were in the habitat wet room. This system permitted scuba cylinders to be filled in the habitat but required them to be hauled up the ladder. The problem with all of these systems is that they required a significant physical effort on the part of the aquanauts simply to fill a scuba cylinder. Although hookah systems reduce these problems, they are good primarily only for work close to the habitat. When an aquanaut is in the middle of an experiment in which time is an important factor or at the end of a long day, a major effort to get more air may be too much trouble. As a result, dives often are cut short, repetitive dives are not made, and all sorts of excuses are offered as to why "I did not go back into the water." Whatever the excuses are, however justified or unjustified, an inconvenient air filling station in a seafloor habitat will seriously impair the efficiency with which a seafloor program is carried out.

In an effort to relieve some of these problems and increase the amount of time spent in the water by the aquanauts, the La Chalupa habitat was designed to permit easy entrance and exit (Fig. 5-19). The large entrance permitted the aquanaut to swim in, sit down on a steel grating, and remove the scuba gear without even standing up. Once the tanks were removed, the aquanaut could simply walk around behind them, attach the filling hose, and charge them without delay. Since the tanks were sitting in about 9 inches (22.9 cm) of water, there existed a ready-made heat sink during filling. Many times the aquanaut would return to the habitat for tools or a top-off. If someone was in the habitat to help, the aquanaut could swim in, sit down, warm up, eat, and have his tanks topped off without ever getting out of the harness.

A diving station in a seafloor habitat should be designed for safety, convenience, and conservation of aquanaut energy. If these goals are

achieved, payoffs will accrue in safety, increased water time, mission effectiveness, comfort, and aquanaut happiness.

Diving procedures are determined by the location of the habitat, the surrounding topography and water conditions, the diving facilities, depth, water conditions, and other factors. Although most habitat programs have been conducted using standard safe diving practices, such as the buddy system and equipment checks, there are some unique aspects of diving from a seafloor habitat. For example, when using scuba during a normal dive from the surface, a good practice is to wear a buoyancy compensator and a quick-release weight belt. When saturated in a seafloor habitat, where one of the most serious dangers is surfacing accidentally, this same practice is not recommended.

A common diving procedure when living in a habitat is to use a hookah (air) hose whenever possible. While virtually unlimited mobility is offered by scuba equipment, the hookah diver has the advantage of time. Aquanauts using hookah can stay in the water as long as they can hold out against fatigue and/or cold. Hookah hoses can fail, however, so aquanauts should always wear a scuba cylinder as an emergency backup.

The thought of becoming lost from the habitat and running out of air is constantly on the mind of most aquanauts. Unlike the surface diver, the aquanaut whose blood and tissues are saturated cannot go up in the event of an emergency such as losing the habitat. In all probability he would be stricken with the bends within 15 minutes and 3 minutes, respectively, when saturated at depths of 50 (15.2 m) and 100 feet (30.5 m). For this reason, a saturated diver working away from the habitat must be continuously aware of his or her dependence on that facility for life support. Any excursions should be planned carefully so that the way back is known and assured.

But to limit lateral excursions to the length of a hose is not always practical and may unduly restrict activities of a scientist attempting to learn about the sea. For this reason, a common procedure for habitat programs is to lay out a grid system of lines, markers, and direction indicators so that the aquanaut can safely make extensive lateral excursions without the danger of becoming lost. Such a grid system also is important to the scientist as a reference for mapping or sampling purposes.

The maximum length of lateral excursions should be determined prior to a mission and be based on the bottom topography, experience of the aquanauts, nature of the grid network, availability of diver communication systems, and general environmental conditions. In some cases, lateral excursions can be extended if prior arrangements are made to have a surface-support boat escort the aquanauts. Surface divers then can resupply air and be available for emergencies.

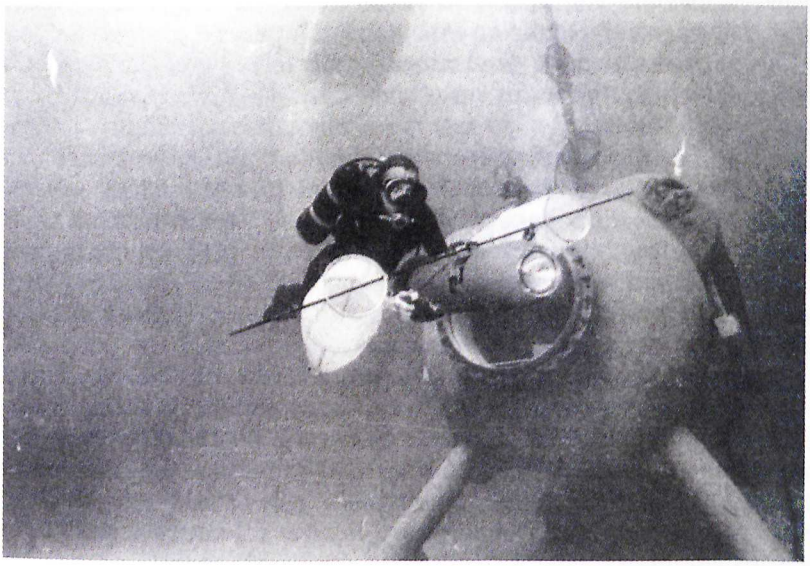

Figure 6-9. Aquanaut using diver propulsion vehicle. (*courtesy of William High, National Oceanic and Atmospheric Administration.*)

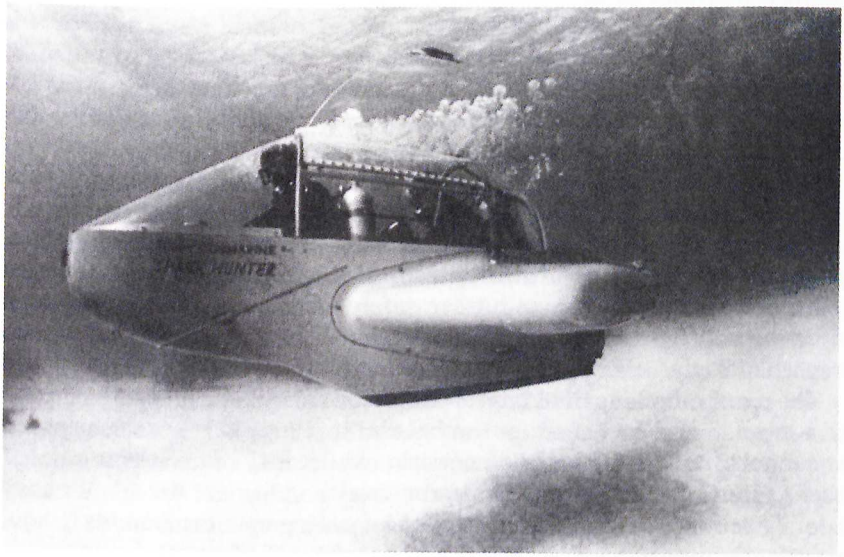

Figure 6-10. Divers using free flooded "wet" submersible. (*courtesy of Dick Clarke.*)

Another method of extending lateral excursions is by using either a diver propulsion vehicle (DPV) or a wet submersible. The DPV is a small hand-held cylinder driven by an electric motor powered from rechargeable batteries (Fig. 6-9). The wet or free flooding submersible is a small vehicle usually designed for two persons that fills with water and is operated by divers using scuba mounted either on their backs or as an integral part of the vehicle (Fig. 6-10).

There are two fundamental problems with using either propulsion vehicles or wet subs in habitat programs. First, experience to date is that the equipment is unreliable; thus it is unsafe to use with aquanauts who are saturated and cannot return to the surface in the event of a malfunction. The second problem is that in spite of the reputation of unreliability, aquanauts tend to place unwarranted reliance on these devices and overextend the distance of lateral excursions. As a result of these problems, propulsion vehicles and wet subs have been used sparingly, and excursions have been limited to a distance from which the aquanauts could return to the habitat unassisted.

In spite of extensive precautions and planning, emergencies inevitably will arise while aquanauts are on diving excursions. Recognizing this, the planners of several habitat programs have included the use of small emergency breathing stations on the seafloor in the vicinity of the habitat. Three varieties of these shelters are shown in Figure 6-11. While designs vary, in each case the shelter is an enclosure in which water is forced out, usually with air from a scuba tank, thus forming an air bubble into which one or two divers can put their heads and breathe. As there rarely were emergencies, these shelters usually were used as a resting place or as a talking station for aquanauts needing to discuss their work while on a dive. Depending on the amount of use, the air was replaced periodically to avoid a CO_2 buildup.

Vertical excursions from a seafloor habitat must be controlled carefully. Excursion tables have been developed that prescribe the duration and depth profiles of both ascending and descending excursions from saturation depths ranging from 30 to 120 feet (9.1 to 36.6 m) (Miller, 1979).

Special precautions must be taken to provide visual and auditory beacons to assist aquanauts in finding the habitat—strobe lights on the habitat, a pinger or beeper, or a special signal that can be picked up by an aquanaut carrying a receiver. Specific procedures for assisting a lost aquanaut must be developed and completely understood by all as the surface is no longer an available haven in an emergency. Factors influencing these procedures are the distance of the habitat from shore, the communication systems provided, availability of surface-support craft, and the location of recompression facilities both on the seafloor and on the surface or ashore.

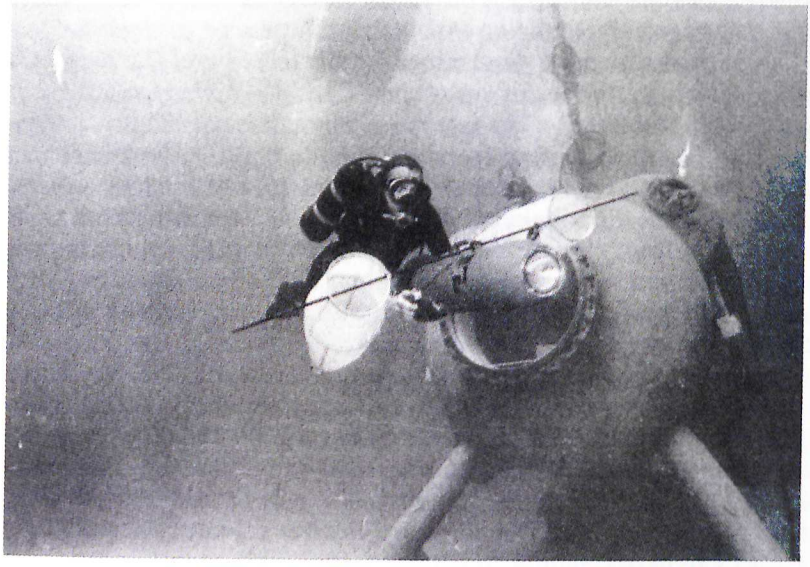

Figure 6-9. Aquanaut using diver propulsion vehicle. (*courtesy of William High, National Oceanic and Atmospheric Administration.*)

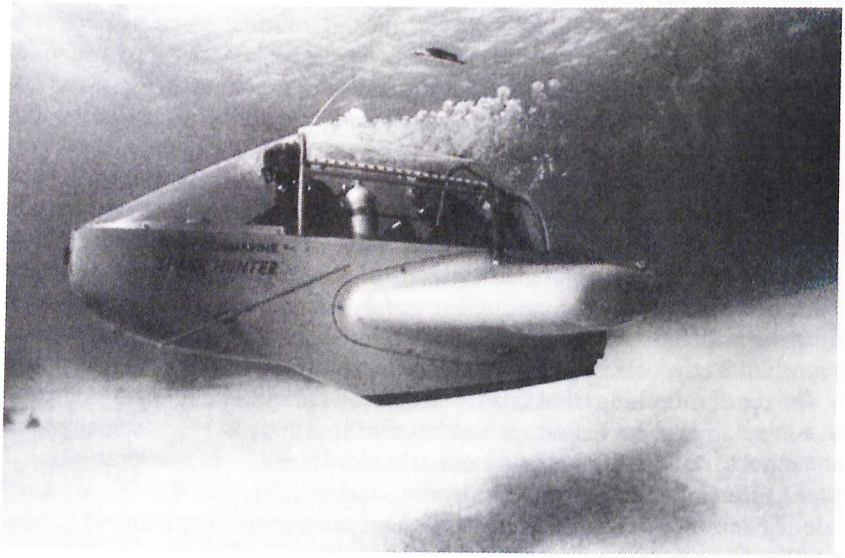

Figure 6-10. Divers using free flooded "wet" submersible. (*courtesy of Dick Clarke.*)

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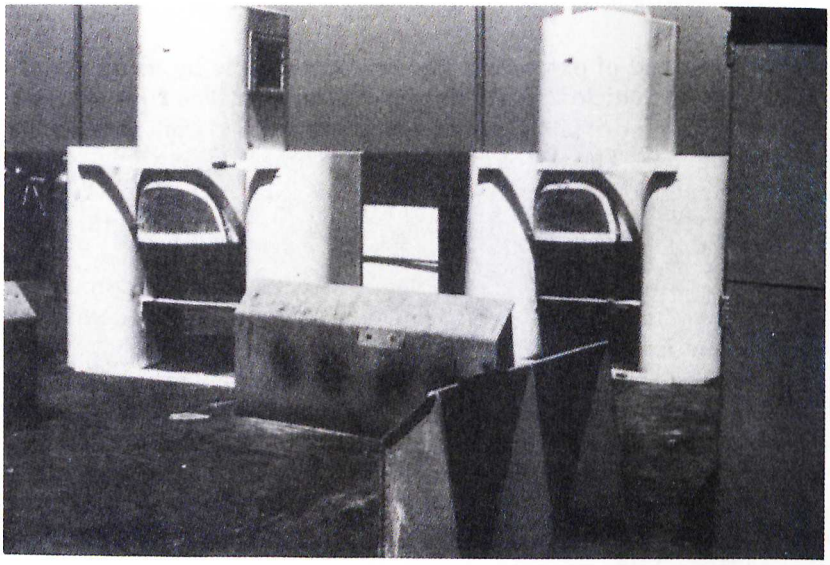

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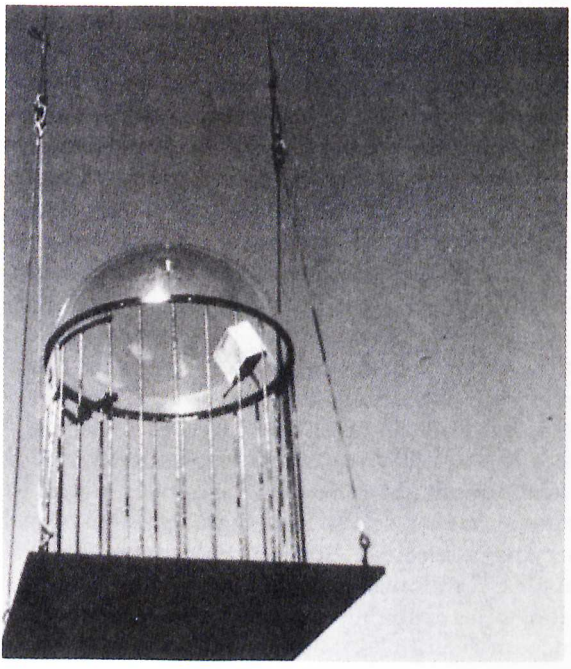

B



C

Figure 6-11. Emergency breathing stations used in three habitat programs. *A:* Sealab II (*photo by James W. Miller*); *B:* Tektite I (*official U.S. Navy photograph*); *C:* Hydrolab

EMERGENCY FACILITIES AND PROCEDURES

A well-conceived habitat program includes contingency plans and equipment for any anticipated emergency. Since habitats have all been one-of-a-kind systems, the brief descriptions of emergency equipment and suggested procedures that follow can serve only as general guidelines. Each future habitat program will have to include individual plans tailored to the needs at hand.

While numerous emergencies may be life threatening to individual aquanauts, a few situations can prove disastrous to the entire habitat and its occupants. One of these is fire. Habitats using air as a breathing medium are susceptible to fire because air supports combustion more readily when under increased pressure. When oxygen content is a fixed volume percentage, the minimum ignition energy varies inversely with the change in pressure (Penzias and Goodman, 1973). A normoxic habitat atmosphere contains a lower percentage of oxygen than an air-filled habitat and therefore is less of a fire hazard. Care must be taken, however, in situations in which oxygen is used during decompression or treatment. At greater depths where helium is used with low percentages of oxygen, fire is even less of a threat, although studies have shown that the rate of flame spread is greater in a helium environment (Shilling, Werts, and Schandelmeier, 1976).

In the event of a habitat fire, the following general procedures should be carried out, although the order of precedence may vary with the situation.

Make a quick assessment of the source of the smoke or flame. (If the source is a movable item, discard it immediately from the habitat if possible.)
Don emergency breathing masks.
Shut off all power except emergency lights and emergency communications.
Notify surface personnel.
Attempt to extinguish the fire with water.
Attempt to remove all flammable materials from the immediate area of the flames. Also attempt to remove smoldering material from the chamber.
Personnel not directly involved in fighting the fire should don diving gear and leave the chamber.
If the fire goes out of control, abandon the chamber, notifying surface personnel of this action if conditions permit. Proceed to available underwater stations and await surface support.

Those wishing more information on fire safety in a hyperbaric environment should refer to sources such as Shilling, Werts, and Schandelmeier (1976) and Schmidt, Door, and Hamilton (1973).

In addition to smoke from a fire, the habitat atmosphere can be contaminated by other substances, including noxious odors, spilled chemicals, carbon monoxide, and carbon dioxide. Depending on the atmospheric monitoring system, such contamination may or may not trigger an alarm. Regardless of how the aquanauts become aware of contaminants in the atmosphere, immediate steps must be taken to correct the situation.

Don emergency masks.
If the source is electrical, secure main power.
If the source is chemical, cover it or wash down spillage with hose.
Notify surface personnel.
If contamination persists, purge the habitat with fresh breathing gas.

In summary, if breathing gas in the habitat becomes contaminated, emergency breathing systems should be available to allow the aquanauts ample time to correct the problem and to purge the habitat without abandoning it. For this purpose, short hookah hoses can be installed in each chamber. This system will provide continuous safe breathing gas as long as there is an uncontaminated supply of air from the surface or from a high-pressure air source on board the habitat. If the source of contamination is on the surface, aquanauts can use individual bail-out air cylinders that should have been placed in each chamber.

Another general emergency aquanauts fear is accidental flooding due either to a port breaking or water rising in the entrance trunk due to failure in the low-pressure air system. An alarm system that senses rising water should be installed in the entrance trunk. Should this unlikely event occur, aquanauts should don emergency breathing equipment and notify surface personnel. In general, aquanauts should not leave the habitat because even in a flooded condition, it is the best source of breathing air, communication, and protection. If evacuation becomes necessary, the aquanauts should remain in a group at the entrance trunk.

Most shallow water habitat systems have a primary power source and an emergency or standby power source. Primary power usually is 110 volts ac; emergency is 12 volts dc. In some systems, emergency power is designed to activate automatically upon failure of the primary source. Momentary power losses may occur during transfer of load from one generator to another, from equipment failures, a damaged umbilical, shorts, or other problem. Should primary power fail, the emergency power source should be activated if this system was not activated automatically by primary source failure. Surface-support personnel should be notified, and aquanauts should stand by to assist in isolating and remedying the cause of the failure.

Most saturation systems have a backup system of communication.

Sound-powered phones that require no external power often are used. In some cases, communication may be possible over diver communication circuits. When a communication failure occurs, communication should be established immediately on a secondary system, the surface should be notified of primary system failure, and attempts made to reactivate the primary system.

Inadvertent surfacing, commonly called a blowup, is a serious hazard facing saturated divers, especially when they are using self-contained equipment and are not physically attached to a habitat by an umbilical or tether. A saturated diver away from a habitat must be extremely careful to avoid any circumstance that would require making an emergency ascent to the surface or that might result in accidental surfacing. If an

Table 6-7. Potential Causes and Indicators of Habitat Emergencies

Emergency	*Cause*	*Indicator*
Structural damage to the laboratory	Ramming, heavy weather	Loud unexplained noise, flooding, drastic change in movement of laboratory, loss of power, loss of communications, hole in hull
Structural damage to life-support buoy	Ramming, heavy weather	Power failure, communications failure, no supply of breathing gases or water to habitat
Flooding	Leak in pressure hull or wet room allowing breathing gases to escape	Rising water in entry trunk, flooding alarm
Fire	Electrical problem, cooking, accidentally ignited diving flare	Smoke, heat, unusual or unexplained fluctuation of power
Contaminated atmosphere	Smoke from fire, buildup of CO_2, failure of scrubber system, chemical spill	Unusual read-out on CO_2 monitor, unusual smells, unexplained drowsiness, headache, unnatural behavior
Power failure	Failure of life-support buoy, failure of umbilical or battery bank, short circuit, fire or flooding	Lights go out, equipment stops
Communications failure	Failure of life-support buoy or umbilical, power outage, damage to communications system through fire or flooding	Inability to communicate with other part of habitat or surface-support team
Accidental surfacing	Lost weight belt, ballast malfunction in a wet submersible, got lost and ran out of air	Above upward excursion limit according to wrist depth gauge, it gets lighter

aquanaut should surface accidentally, however, every effort should be made to return him to the saturated depth either by placing him in a recompression chamber or by escorting him back to the seafloor. Detailed procedures need to be provided in each program, as safe practices will be dictated by the support facilities available, the depth of the saturation exposure, and other operational conditions. Table 6-7 summarizes the principal types of emergencies, their most probable causes, and indicators.

DECOMPRESSION FACILITIES AND PROCEDURES

Decompression following completion of a seafloor mission has been achieved in several different ways. In the Hydrolab and Helgoland programs, the aquanauts were decompressed in the habitat on the seafloor. This required sealing the outer hatch of the entrance lock and reducing pressure according to the decompression schedule by venting breathing gas to the surface. When such a system was used, decompression was controlled by the aquanauts from inside the habitat. Once decompression to a surface equivalent pressure was completed, the habitat was recompressed to ambient pressure to permit opening the hatch, and the aquanauts immediately swam to the surface. Over 500 aquanauts have decompressed safely using this technique from depths of 40 to 60 feet (12.2 to 18.3 m) during the Hydrolab programs.

Aquanauts in the Aegir and La Chalupa programs also decompressed inside their habitats. In both cases, however, the habitats were brought to the surface with the aquanauts inside and towed to shore, where decompression was completed at dockside. An advantage of this system is that aquanauts could be transferred quickly to a backup shore recompression facility in the event of a failure of the habitat system. A potential disadvantage of this method, although it has not been a problem, is that aquanauts must be towed in the open sea while under pressure. This danger can be obviated by leaving the habitat on the seafloor during bad weather or bad towing conditions.

The Tektite program used still a different technique. For both Tektite I and II, aquanauts swam about 300 feet (91 m) at saturation depth and entered a closed diving bell. The bell then was raised to the surface and mated to a DDC (Figs. 4-22, 4-23). This same technique was used in 1965 during the Sealab II program where a pressurized transfer chamber was entered by a ten-man team on the seafloor, raised to the surface, and mated with a DDC (Fig. 4-5). The use of pressurized transfer chambers for transporting aquanauts from the surface to the seafloor and back again has been used extensively in commercial diving operations since 1966.

In 1972, a project conducted off the coast of Miami, Florida, called FLARE (Florida Aquanaut Research Expedition), used the Edalhab habitat (Fig. 6-12). This habitat accommodated three aquanauts and was used at a depth of about 45 feet (13.7 m). As shown in Figure 6-12, the habitat was supported by a large vessel located directly overhead. In this program, the aquanauts, on completion of the five-day mission, swam to the surface, climbed aboard the surface vessel, and entered a small decompression chamber. Elapsed time from leaving the seafloor to



Figure 6-12. Artist's conception of project FLARE showing Edalhab habitat and support ship *LULU. (courtesy of National Oceanic and Atmospheric Administration.)*

recompression was about 2 minutes. This technique is possible because of laboratory work conducted as part of the Tektite program that demonstrated that from a saturation depth of 50 feet (15.2 m), an aquanaut who surfaces immediately has at least 15 minutes before bends symptoms occur (Edel, 1970).

Another technique for decompression was used in the Polish Medusa (1968-1971) and the Israeli Neritica (1978) programs. In both instances, the habitats themselves were raised to the surface, with stops at designated depths for decompression. Such a technique is satisfactory for habitats not designed as pressure vessels if the seas remain calm.

The most comfortable method of decompression is inside the habitat on the seafloor. Facilities are more spacious, and aquanauts can continue to enjoy the beauty of the surrounding sea and, in some cases, continue to collect data on seafloor experiments. Decompression on the surface, either in a chamber or a habitat, at least in tropical climes, chronically has presented the problem of uncomfortably high temperatures.

In addition to primary decompression facilities, secondary or backup decompression equipment should be provided for habitat programs. Most of the major programs have included a backup chamber on shore or on board the support ship. Backup systems should must include ample supplies of breathing gas and oxygen for both scheduled decompressions and for emergency use. Required equipment and procedures for safely operating decompression chambers are described in Miller (1979).

An interesting double backup system for handling decompression emergencies was employed for the La Chalupa habitat. It included a 60-inch (152.4 cm) shore-based chamber and two emergency escape capsules mounted on the habitat itself (Fig. 4-46). These escape capsules served several purposes. At sea, when under tow, they served as conning towers to keep breaking seas from entering the habitat. On shore when aquanauts were decompressing, they served as double-lock entrances to permit entry by support personnel during decompression when the habitat was pressurized. In the event of an emergency during a mission, each capsule could hold two aquanauts and be released to the surface, where it could be picked up by a Coast Guard helicopter or support craft (Fig. 4-49).

Much has been learned about the design, life-support requirements, and operation of seafloor habitats since the first aquanaut lived in the sea in 1962. The technical knowledge gained, when coupled with the concurrent advances in technology, should be of immense benefit when planning and developing future undersea programs. But it also is important to examine the personal side of living in the sea if a balance is to be achieved in our understanding and appreciation of the potential offered by seafloor colonization.

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Chapter 7

Personal Glimpses into Undersea Living

WHY LIVE IN THE SEA?

Studying the sea from the surface compares to studying a forest from an aircraft hovering above dense clouds. You can lower nets, baskets, hooks, robots, and television cameras, but how much more effective to walk through the forest, to camp for days, weeks, or months, to become an integral part of the environment until you begin to understand it as do its other inhabitants. Why then do we feel comfortable in learning of the sea by making brief visits or by floating on its surface? Is it the potential discomfort, the danger, the reluctance to try new ways, or is it perhaps the fear shared by many in the world of science that concepts long held may be proved wrong by firsthand encounters? Perhaps it is all of these.

We live in the sea to learn, to become accepted as part of it, to overcome our fears and misconceptions, and to gain knowledge necessary to protect it and use its resources wisely. Dive briefly beneath the sea's surface, and undersea life will avoid you much as wildlife avoids the occasional hunter or hiker. This fact led to early concern about the impact of a seafloor habitat on behavior of local marine life. Would aquanauts find themselves in a no-man's marine land? Quite the contrary. A habitat quickly assumes the role of an artificial reef and attractant rather than a marine life repellent.

This settling-in period is fascinating. Territoriality of fish is well known, but the speed with which it occurs is one of the surprises of habitat programs. Within minutes following emplacement of La Chalupa, even before the sediment had settled, each corner of the barge was claimed by some form of marine life that immediately took defensive action against all intruders, including the aquanauts. Within a few more hours, every nook and cranny was staked out as if the habitat had been there for years and the human intruders were accepted as part of this alien world.

As fellow inhabitants, aquanauts are able to discover unexpected facts about their neighbors that are difficult or impossible to deduce from the surface. For example, a totally unknown character trait of the male spiney lobster, primarily a nocturnal animal, was discovered during a Tektite I mission. A beeper attached to the lobster's carapace enabled an aquanaut to follow him around without affecting his normal behavior pattern. It was found he may cover a distance as great as 1000 feet (304.9 m) in one night and call on several female lobsters during his travels, after which he returns to his lair to rest until the next night. Studying lobsters from the surface during daylight hours, this element of their behavior had gone undetected.

Comparable data can be obtained about other sea dwellers when scientists are able to spend long periods in the water. This freedom to explore, to study life in its natural surroundings, to return to the same spot time after time, and to analyze specimens without the reduction of pressure required when bringing them to the surface are but a few of the benefits and reasons for living in the sea.

THE AQUANAUTS

We have defined an aquanaut as a person who has lived at least twenty-four continuous hours on the seafloor. Although the precise number of aquanauts is difficult to pin down, it is estimated that about eight hundred persons in the world qualify for this title. The eight hundred in this group will give eight hundred different answers to the question, "Why live in the sea?" ranging from "because it's there" to "we must study the load-bearing characteristics of the seabed." The reasons given most frequently by the one hundred to two hundred aquanauts we know personally are: exploration, search for knowledge, adventure, and to become part of an alien world. Humans electing to live and work under hazardous conditions elicit certain behavior patterns and performance characteristics.

First, let us look briefly at the composition of other groups who have functioned under comparable conditions, such as polar wintering-over parties composed of scientists, engineers, technicians, and students who

may spend long periods in an isolated, dangerous, and confined environment. On some polar expeditions, people have lived for several days in small, over-snow vehicles while traveling over an inhospitable Antarctic environment to explore and collect scientific data. Air drops made to these explorers are much the same as pot drops to aquanauts. The cold, the wind, the danger of becoming lost from the only source of shelter in many ways are comparable to the aquanaut deep in the sea with a single haven, the habitat, to return to.

Also comparable in makeup, and perhaps more familiar to aquanauts, is the oceanographic research vessel on which scientists and engineers may spend extended periods at sea. Many aquanauts participate routinely in such cruises. The age range for polar parties and oceanographic teams is similar to that of aquanauts, although the mean age for aquanauts is lower. In all three groups, participants range in age from 20 year-old graduate students and technicians to senior scientists in their sixties and seventies. Although the oldest aquanaut we know of is a researcher who took part in a 7-day saturation dive in Hydrolab at the age of 56, on a worldwide basis, the average age of aquanauts is between 30-35.

Of the approximately eight hundred worldwide aquanauts, many have participated in more than one seafloor mission, with some taking part in four or five missions. As of this writing, the aquanaut with the most accumulated time on the seafloor is Dr. J. Morgan Wells of the NOAA, who has lived in six different habitats for a total of 175 days on the seafloor.

The physical condition of aquanauts has varied considerably both between programs and within a specific project. Military programs have required aquanauts to be in good physical condition and possess considerable diving experience. On the other hand, early civilian undersea programs used aquanauts who were experienced in special areas but in some cases had limited diving experience and may not have been in particularly good physical condition. The habitat engineer on the female team for Tektite II, for example, had no diving experience at all prior to being selected and was taught to dive in order to take part in the mission. Cousteau's approach for the selection of oceanauts for Conshelf II was similar.

> Everyone on the team had volunteered as an oceanaut. Since the five-man party was to be a working marine research team headed by Professor Vaissiere, men were selected with appropriate qualifications "and we did not specially care whether they were experienced divers or not. Age and physical condition didn't matter much either: the oldest man in the party was cook Pierre Guilbert, forty-three, who is stout, un-athletic, and has mild arteriosclerosis. All five men were married and had children. Pierre Vanoni, a former customs inspector, had dived only a few times before he

went to live inside the sea; Andre Folco, a valuable mechanic and engineer, also had a slim underwater record. The only professional diver in the group was Claude Wesly, thirty-one, whom the oceanauts called l'ancien, the veteran, because this was his second residence on the seafloor. He had been in Conshelf I with Albert Falco." (Cousteau, 1964, p. 7).

The first female aquanaut was Madame Jacques Yves-Cousteau who spent 4 days in the Starfish House of Conshelf II in July 1963. After 5 months of hard work on board *Calypso* in support of the surface team, she decided to join the team on the seafloor, donned her diving suit, and went down to the 36-foot (11 m) depth. She stayed with the team to the end of the mission and through decompression. It was to be 4 years later, in the summer of 1967, before the next female aquanauts lived in the sea during the Ikhtiandr program in the Soviet Union. On this occasion, Mariya Barats, a physician, and Galina Guseva, a graduate student, spent 3 days at a depth of 39.4 feet (12 m) (Guseva, 1967). Two years later, Silvana Polese, a 17-year-old aquanaut, lived in the Atlantik habitat in Italy.

The first all-female team of aquanauts to live on the seafloor was during the 1970 Tektite II program. The performance of the five women during the two-week mission confirmed that female aquanauts could perform as effectively as males in a scientific saturation diving program. Since that time, selection of teams and aquanauts for scientific missions for habitat programs in the United States has been made on the basis of diving experience, physical condition, and scientific background, irrespective of gender. Approximately 25 to 30 female aquanauts have lived on the seafloor, although to our best knowledge, Ikhtiandr, Tektite II, La Chalupa, Hydrolab, Atlantik, and Conshelf II are the only programs in which females have participated as aquanauts.

Aquanauts as a group form a highly qualified and educated population. In the United States, they usually come from middle-class or upper-class, stable families. Most are married and well educated. Studies of personality profiles of over 50 aquanauts of the Sealab II and Tektite I and II programs revealed that these profiles were identical to those of the climbers of Mt. Everest and very similar to the astronauts of the U.S. space program (Helmreich, 1971). Scientists undertaking hazardous but professionally rewarding tasks seem to have a similar constellation of values characterized by high theoretical and aesthetic values, low religious values, and average social, economic, and political concerns. These studies found that gregarious aquanauts scored significantly higher in productivity during seafloor missions. Data concerning productivity under hazardous conditions also have been collected during Sealab II, from an analysis of performance of military pilots during combat, during Tektite I and II, and in the U.S. space program. One particular finding is

interesting though unexplained. The data consistently show the performance of firstborns in highly stressful environments to be inferior to that of later-borns. The data also show, ironically, that firstborns volunteer significantly more for such assignments. In the Tektite program, where stresses were low or moderate, firstborns outperformed later-borns. The implications of these findings for selection of future aquanauts for highly stressful missions are not clear.

In general, aquanauts around the world represent a cross-section of the scientific and technical community. The earliest aquanauts were inventors, engineers, technicians, sailors, and physicians whose goals were to demonstrate that useful, productive work could be accomplished safely while living in the sea. As improved technology and habitat design have made living on the seafloor less physically challenging, the nature of those choosing to do so also has changed. The pure adventurer has become less enthralled and the serious scientist more interested. The trend to more participation by biologists, geologists, ecologists, and other related marine scientists is natural and consistent with experience in most other fields of exploration and science. This trend should continue, resulting in seafloor habitats' becoming a natural extension of terrestrial laboratories. Scientists working in the sea should become as commonplace as in any other natural environment.

FIRST NIGHT ON THE SEAFLOOR

The first day on the seafloor usually starts in mid-afternoon, which allows 3 to 4 hours of daylight to get organized, check out systems, and set up housekeeping. You're pretty busy with routine and unexpected tasks, so dusk sneaks up before you realize that enough time has gone by to preclude a return to the surface without a long decompression. You're on the bottom without a speedy escape hatch. This is, in some respects, a moment of truth. You're now linked to the habitat and your fellow aquanauts in a life-dependent symbiosis. You ask yourself if all the systems will work. What are all those strange noises? Will the habitat leak? Will I get lost and be unable to return to the habitat? As darkness falls, strange shapes drift past the ports, studying the intruders in their domain.

If the habitat has been in place for a while, moving in is simply a matter of arranging gear in the incredibly small space allotted and preparing for the next morning's dive. If the habitat is new, there is much more checking out to do and perhaps a little more subliminal uneasiness about the whole idea. At this point, the lights may be turned on, and the alien world of the seabottom unfolds. The ecstatic feeling of being there knows

no national boundaries. In conversations with aquanauts from France, Germany, Russia, Bulgaria, Canada, and the United States, reports are all the same: the first night undersea is an experience not to be forgotten. You've been diving before and you've seen fish before, but the feeling of living among them, the knowledge you'll be sleeping here and will wake with the sea and its creatures still around you, is totally new. You spend hours watching shapes from the distance resolve into creatures leading lives in an element you are not designed for but they are. How beautifully designed for their element is part of the fascination that keeps you at the port long after you should be asleep. At this point, fatigue may force you to your bunk, but there are other possibilities.

If you were a Russian aquanaut in one of the Chernomor programs, your first night would be different. Because of mechanical problems one year, the first night was spent in the habitat at the docks of Zhdanovskiy ship-repair base. If you were with Conshelf III, you would have remained inside the habitat under pressure for over 24 hours at shore while repairs made necessary by storm damage were being made because you were already saturated. When problems such as these arise, aquanauts usually are among those attempting to solve them. By the time everything finally is in readiness and the team is secure on the seafloor, it is time to relax a little. With the months of preparation out of the way and the actual emplacement and checking out accomplished, the incredible feeling, "I'm actually living on the bottom!" takes over.

Training cannot prepare one for the strange noises that become audible in the quiet of the night—the gurgling in the entrance trunk, the creaks and groans of minute shifting of the habitat, sounds of fish hitting the hull outside. If swells are high and the habitat not too deep, constant alteration of pressure caused by change in water level in the entrance trunk requires continual clearing of the ears.

The feelings of one aquanaut during his first night on watch duty are expressed by M. A. Rostarchuk, a newspaper correspondent with *Izvestiya,* who was a member of the Russian Chernomor team in August 1968:

> My first watch. Deep night. I sit at the "Chernomor" control panel. The sticky, moist silence is broken only by the infinite gurgling and rushing of air bubbles from the exhaust valve through some microscopic slits. If one turns out the table lamp, there is total darkness—the windows are as dark as the walls. Only the hands, scales and levers of the toggle switches show up on the control panel with a lunar fluorescent color. In the sealab we walk about in the lightest conceivable clothing—swimsuits. But one of us has to sit at the control panel, take the microphone of the loudspeaker communication system with the pontoon, and he immediately assumes a rigorous

naval appearance. My comrades are sleeping heavily. During the next four hours as watch officer, I will be responsible for their lives. And, although virtually nothing out the ordinary can occur, the time of responsibility completely drives sleep away: after all, all around, behind these walls, there are masses of water. [Podrazhanskiy, Rostarchuk, and Stefanov, 1973, p. 298]

STRESSES AND STRAINS

The concept of stress and its definition have been debated in the literature for years. Extensive studies have been performed in which the experimenter manipulated the environment in a manner designed to produce a disruption of behavior or stress. A problem with many of these experiments was that a stressful stimulus as defined by the experimenter may not have been perceived by the subject of the experiment as being stressful. Consistent with the tenet that stress is a perceived state, the definition of Basowitz, et al. (1955, pp. 7-8) is perhaps apropos within the context of undersea habitats: "We should not consider stress as *imposed* upon the organism, but as its *response* to internal or external processes which reach those threshold levels that strain its physiological and psychological integrative capacities close to or beyond their limits." Because life in an undersea habitat offers the experimenter an opportunity to study the effects of real danger and perceived stress, the behavior of the early aquanauts was studied extensively. As pointed out by Radloff and Helmreich (1968, p. 18) "There was little doubt as to the stressful nature of Sealab life. The very nature of the project permitted us to anticipate with certainty the occurrence of stress reactions. Thus, the possibility that subjects would not be under real stress was not an issue."

The sources of stress and the responses of the aquanauts to these sources varied widely among programs with respect to severity and type. Physiological stresses resulted from a variety of sources. The humidity in many habitats was extremely high, routinely attaining and remaining at levels of 85 to 95%. Inability to escape to a dry place was a constant source of irritation. The high humidity in some programs, such as Conshelf III, resulted in wet beds. Vanoni, one of the Conshelf III aquanauts, commented that the honeycomb latex mattresses were becoming moldy and the sheets were like wet towels that had been dropped on the beds by accident.

Another problem was the cold. Even in tropical waters, extended dives resulted in the need for an adequate rewarming capability in the habitat. A hot shower followed by a brief warmup in bed under a blanket was a

favorite solution. If the habitat was filled with a helium-oxygen breathing mixture, the cold factor was multiplied many times over. Perhaps the most serious incident resulting from a cold habitat was during the 516-foot (157.3 m) dive of the Aegir in June 1971, described in Chapter 6.

General fatigue experienced by aquanauts in some of the early habitat programs was partially a result of fitful sleep patterns. In many cases, the loss of sleep was due to uncomfortable beds, cold, the need to stand regular watches during the night, and the subliminal attention paid to strange noises or variations in routine noises, which could indicate a malfunction. Aquanauts of Sealab II reported serious difficulties in getting to sleep. A quote from one of the aquanauts reflects the problem:

> I would like to go down again, but not right away. It takes a lot out of you, like sleep. I got only ten hours sleep the whole time I was down there. That was my only problem, just sleep. I ate good . . . everyone had trouble sleeping. I was relaxed, it wasn't that you were bothered that way. You would lay there and you would toss and turn and you felt like you were sweating, you were hot and you were cold. [Radloff and Helmreich, 1968, p. 75]

By contrast, the aquanauts of Tektite I experienced no severe loss or disruption of sleep. Instead of obtaining less sleep, they slept longer and deeper than normal as measured with a special sleep cap with electrodes connected to an electroencephalograph. Even though they had more sleep, they generally desired more. This need could have resulted from the diving schedule, the hyperbaric nitrogen-oxygen saturation environment, or the absence of rigid time schedules for retiring and arising (Naitoh, Johnson, and Austin, 1970). The 46 aquanauts in Tektite II did not report sleep problems and averaged about 8 hours of sleep per night. Hydrolab and La Chalupa aquanauts similarly did not report sleep as a significant problem. Generally, problems associated with sleep seemed to have been more prevalent in habitats in which the breathing gas was helium-oxygen. Whether this is due to the greater narcotic effect of nitrogen under pressure, the fact that beds were more comfortable, the chilling effect of living in a helium environment, or to other factors has not been determined.

In many early habitat programs, significant efforts were invested in gathering medical and physiological data from the aquanauts before, during, and after a seafloor mission (Fig. 7-1). While the need for such data was understood, its collection during the mission often was a source of irritation for the aquanauts. In Conshelf I, physicians entered the habitat twice a day to conduct a 2½-hour medical examination. The evening examination was eliminated on the fourth day, much to the



Figure 7-1. Brain wave measurements being made on Bulgarian aquanaut Nick Dukov during Chernomor '74. *(Courtesy of L. N. Klissurov, Institute of Oceanology, Varna, Bulgaria.)*

delight of the two aquanauts. In the Sealab and Tektite programs, daily examinations required the aquanauts to obtain samples and specimens from every orifice of the body. They soon came to regard such examinations as interference in their mission and to be demeaning. They became the source of many complaints and much humor. In general, the results of medical studies conducted during undersea habitat programs have been negative, prompting George Bond to state at a 1966 meeting:

> Since 1957, when we first commenced our laboratory work on the physiological problems of prolonged exposures to high pressures of synthetic environments, through all the years of the animal and human experimentation culminating in Sealab I and Sealab II, we have examined almost every imaginable physiological parameter and we have not found any serious deviations from the normal in man or in animals. This is not to say that such data are absolutely reliable when one exposes men in such a fashion. Indeed, we see some trends which would indicate that if the exposure is increased to 60 to 90 days one might possibly get into trouble. In general we

> see two trends. We see a type of stress response during the first 3 days, which sometimes lasts as long as 5 days of exposure to this new environment. It does not represent a change beyond the normal range, but goes to the limit of normal. After about 5 days all of our human subjects and animals alike tend to come back toward the baseline. However, after 15 days of exposure we now see a drop below the baseline approaching the lower limits of normal. [Bond, 1967, p. 81]

The most prevalent medical problem in undersea habitats has been ear infections. Humid environment and constant exposure to water create an ideal environment for culturing bacteria. In addition to pain and irritation, ear infections can result in as much as 50% reduction in dive time. After months of preparation, the inability to carry out the program because of an earache can be maddening. A related medical problem experienced in several habitat programs that is also attributed to the high humidity is the slow healing of wounds. While not debilitating, it was a constant source of annoyance to the aquanauts. Because early studies did not reveal any serious medical consequences of seafloor habitation, habitat programs since about 1971 have not included extensive medical studies. Except for an occasional research project, medical programs in undersea habitats now are limited to a thorough examination before the mission and a brief checkup following completion.

Another source of stress for some aquanauts is that the oxygen content in some habitats is insufficient to support combustion, thereby making smoking impossible. About 11% oxygen is needed to keep a cigarette alight. Though a blessing to some, this fact of seafloor life has been a source of stress to regular smokers. The lengths to which a smoker will go for a puff or two was demonstrated during Tektite I, when one of the aquanauts would fill a plastic bag with air from the high-pressure air system, put his head inside, and light a cigarette.

Helgoland smokers found smoking easier. One area of the habitat had a vented fume hood and an outlet for high-pressure air close by. This was referred to as the smoking room, though not formally. The smoker could go to this room, turn on the high-pressure air, open the fume hood, and light up. The hood carried smoke out of the habitat so no contamination would take place. The German aquanauts also used the seafloor igloo (Fig. 4-35) for smoking. In a 1976 mission the igloo became so contaminated with smoke that it was not usable as an emergency air breathing station. Similar ingenuity was shown by the smokers in Hydrolab who would go outside and smoke in the air-filling station, which had a bubble of air from the shoulders up.

The problem of voice communication in a helium atmosphere was a

constant source of stress even with the use of electronic speech unscramblers. An excerpt from an interview with a Sealab II aquanaut illustrates the problem:

> It became easier to understand people in about 2 or 3 days, and after about 7 or 8 days, it was very easy to tell who was talking without turning around and looking in almost all cases. However, I noticed that there was still a great deal of difficulty at the end to get across fine points or to use an uncommon word. This, I think delayed us a hell of a lot in deciding what we were going to do on the diving, making sure what you were going to do on a specialized process. I felt there was still a communication problem at the end—added to this, there was a lot of noise in the lab. [Radloff and Helmreich, 1968, pp. 69-70].

While verbal communication in a nitrogen atmosphere at depths of, say, 100 feet (30.5 m) is far superior to that in a helium atmosphere, there also are communication problems, especially when speaking with the topside support crew.

As if communication under normal conditions was not difficult enough, one of the crews in Tektite II decided to create ingenious new problems. During an evening meal, they carried on a normal conversation with hand and arm gestures and moved their lips as if speaking but without uttering a sound. The support team, monitoring them on TV, assumed a communication system failure. This created some stress on the surface but relieved some in the habitat.

An additional source of stress associated with habitat living traditionally has been poor layout of space and overcrowded conditions. In most habitats work space and living areas have been inadequate. Cramped living, absence of privacy, and a place to call one's own have been characteristic of many habitats. While most aquanauts have been willing to put up with discomfort, crowded conditions, and long schedules, a common complaint has been the lack of even a small area in which to keep personal items. Designers of future habitats should insist on including individual storage areas, no matter how small the system dictates they be.

In spite of the many dangers, frustrations, and disappointments, the esprit de corps of almost every team to saturate on the seafloor has been good, reflective of a very high level of motivation on the part of the aquanauts to make their mission successful. Although for some the reason for high morale may have been the pioneering nature of the undertaking or being the center of attention, pride of accomplishment and the joy of taking part in important work played a key role in many

early programs. As seafloor habitats became more commonplace and the dangers fewer, there was a shift toward pride in carrying out valuable scientific work and in collecting data never before obtained.

Another factor in maintaining team spirit on the seafloor for individual aquanauts is acceptance by teammates. Most aquanauts make tremendous efforts to get along well with fellow aquanauts. People who have clashed previously on the surface often get along well while on the seafloor. Little courtesies may be extended and cooperative efforts made that would have been ignored under normal conditions. No one wants to foul up a mission because of personality difficulties. As Radloff and Helmreich (1968, p. 106) pointed out, it is difficult to overestimate the importance of group acceptance or rejection in determining adjustment to isolated and dangerous environments. They quote a statement of a member of an Antarctic wintering-over party: "If the rest of the guys get fed up and stop talking to you, that's worse than if they went off and left you in a crevasse."

Many aquanauts in recent years have come from the ranks of marine scientists and received some of their field training aboard oceanographic research vessels. In many cases, enormous conflicts occur on these vessels caused by stress in an isolated environment. A study published by Bernard and Killworth (1973) cites examples of discord between scientists and crew. In one instance $50,000 worth of equipment and two years of data were thrown overboard by the crew following a dispute over the use of a refrigerator for specimens and beer. The closest analogy to this situation known to the authors occurred during the 15-day mission of Team 3 of Sealab II. Three scientists were living in the habitat with seven navy personnel. The task of the scientists was to collect and analyze specimens and to observe marine life. The sailors were there to conduct several salvage experiments involving heavy manual labor. The sailors regarded the scientists as goof-offs because they didn't participate in the hard work. To the scientists, the sailors were a source of harassment and an interference in their scientific studies. Even so, the situation was not allowed to interfere with the missions. Each group controlled their hostility, and all planned experiments were carried out.

On one occasion during a Hydrolab mission, the seafloor program was aborted a day early because of strong hostility among the aquanauts. Ironically, the three men had been close friends prior to the mission. Later the same three again formed a Hydrolab team to do more work and perhaps to prove to themselves that they could get along while living together on the seafloor, which they did.

When conflicts do occur in seafloor programs, the schism usually develops between habitat teams and surface-support personnel. In the programs of Cousteau, Sealab, Tektite, and Chernomor, there seemed to

be about a 2- or 3-day adaptation during which the crew adjusted to the isolated nature of their surroundings. Following this, if there was to be conflict, an "us versus them" feeling could be detected. What were originally considered normal communications from topside now were regarded as excessive interference. Simple questions from the surface were viewed as unwarranted demands on time and energy. Underwater teams might develop a feeling that the support teams didn't really understand their problems so shouldn't tell them what to do.

In Sealab I, Conshelf I, and Tektite I, steps were taken to restrict unnecessary communication from topside to avoid antagonizing the aquanauts. In Conshelf I, Albert Falco, when writing in his diary about relationships with topside, wrote, "Also there has got to be telephone discipline. They ring us up from the island and the boats, often on unimportant matters. This first experiment is too mechanized. I see the next one differently. They should give us huge tanks of compressed air and say: There are fish all around you. Get on with it. If you need anything, call us. Otherwise, we'll ring you only on vital business." (Cousteau, 1964, p. 235). During the 1969 mission of Chernomor, when asked what was the most difficult thing about underwater life, aquanaut V. Nikolayev responded by saying, "Fifty times a day, repeating by telephone to those we knew and did not know and at the most inconvenient times, that we felt excellent and that all systems were operating normally" (Podrazhanskiy, Rostarchuk, and Stefanov, 1973, p. 139).

On the sixth day of their 60-day mission, Tektite I aquanauts cut off communication with their support team for several hours as part of a dispute over interference with the scientific program. The on-scene naval commander was on the verge of prohibiting communication from being initiated from the surface when the matter was resolved by an agreement on a communication schedule.

Many aquanauts have reported a day or so of mild depression after 2 or 3 days on the bottom. This temporary letdown is not surprising because the first day or two is spent with the busy work of setting up and settling in. But then spirits rise, and a period of high productivity follows.

DAILY LIFE ON THE SEAFLOOR

Aquanauts tend to get along better together on the seafloor than when working and living on the surface. An important element of this conviviality is the development of in-humor, seemingly dull and mundane incidents that become the source of much laughter. Standard phrases with purely local connotations develop quickly. This humor can be carried over

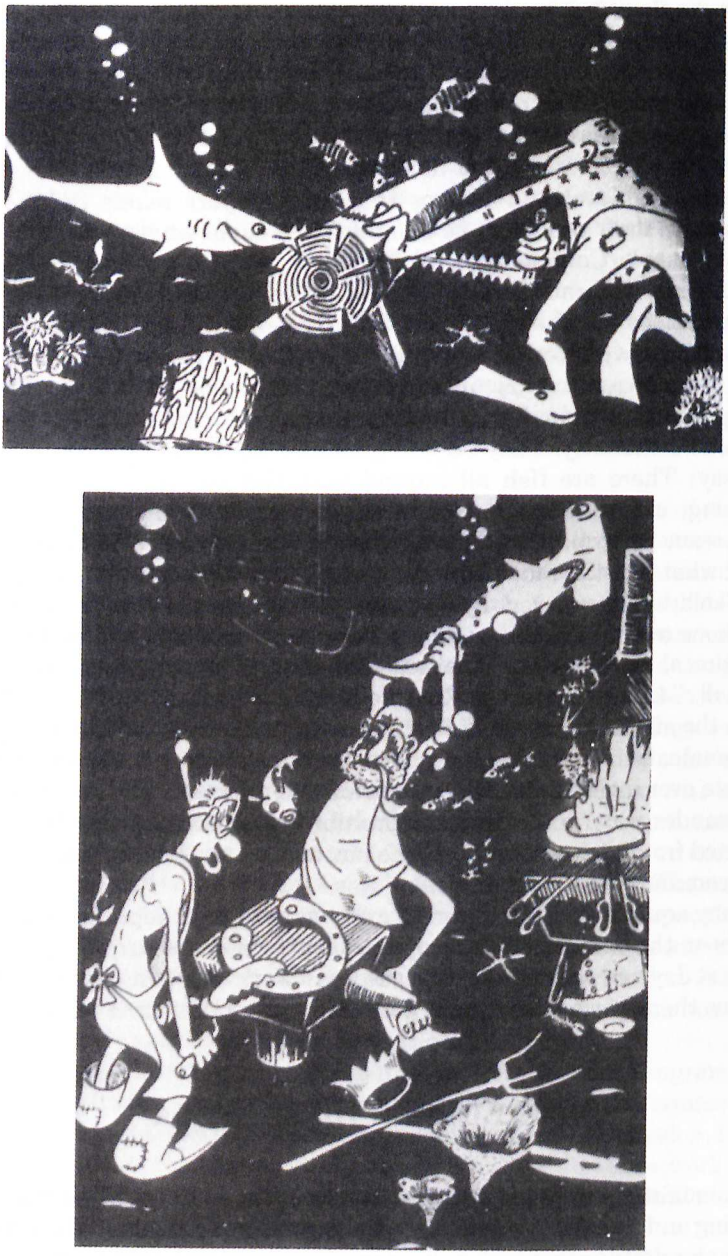


Figure 7-2. Chernomor cartoons showing aquanauts working with local inhabitants. *(From A. Podrazhanskiy, M. Rostarchuk, and G. Stefanov, 1973, March of the Chernomor, Joint Publication)*

into creation of habitat cartoons, as shown in Figure 7-2 where the Soviet aquanauts in Chernomor are depicted taking full advantage of their neighbors. In addition to local humor as a source of entertainment, many aquanauts choose to play games to while away the time after work hours. Chess was popular in many programs and was played both inside and outside habitats.

Daily life in a habitat often includes some form of musical activity: playing tapes, radio, or an instrument such as guitar or ukelele (Fig. 7-3). Singing tried in a habitat filled with helium-oxygen, will sound humorous. Imagine a chorus of chipmunks doing "Amazing Grace." Another challenge is learning to whistle because beginning at about 50 feet (15.2 m), the increased density of air makes whistling almost impossible. During the entire 60-day Tektite I mission, only one aquanaut was able to whistle. In other missions aquanauts were able to whistle, although with considerable difficulty, at depths as great as 100 feet (30.5 m).

The surface-support team, frequently seen as a necessary interference in habitat life, is the natural target of aquanaut humor. In Tektite I, however, aquanauts sometimes seemed to crave almost excessive communication with topside. Ironically communication in this program was discouraged because the psychological program called for study of human behavior in an isolated environment, and communication was to be

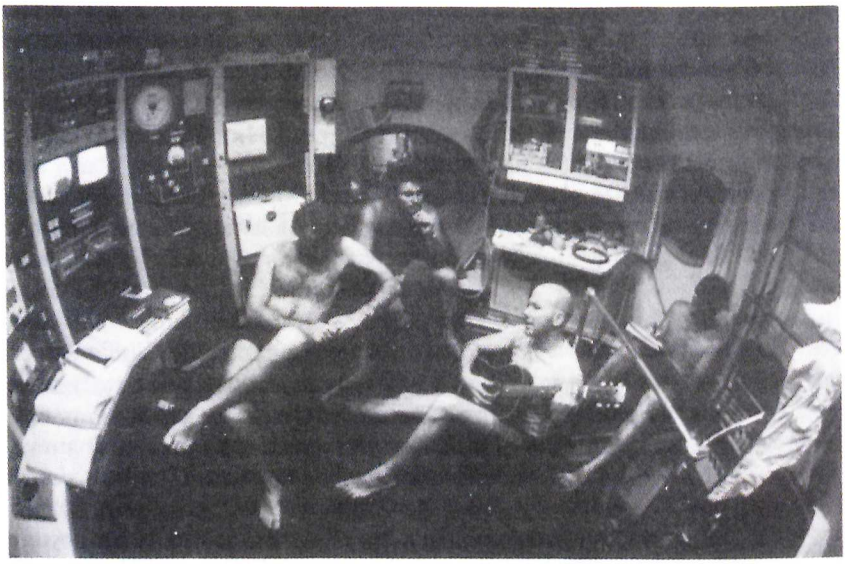
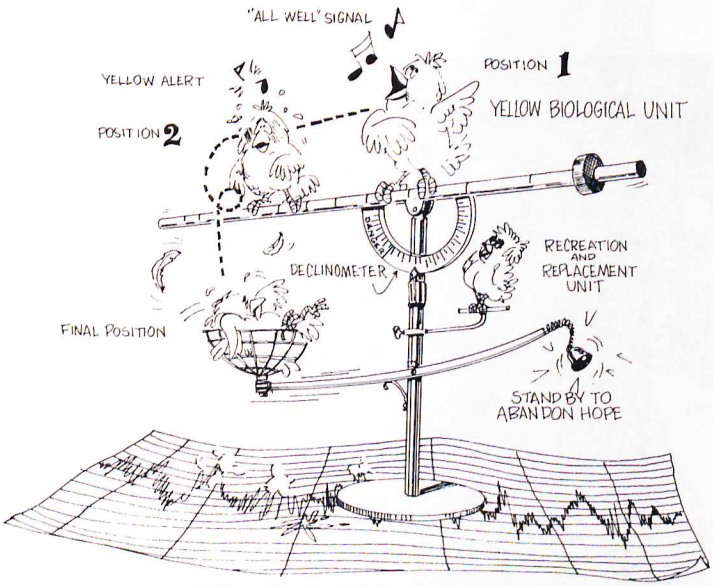


Figure 7-3. Relaxing in Tektite II. *(By Bates Littlehales; © 1971 National Geographic Society.)*



A


"ALL WELL" SIGNAL
YELLOW ALERT
POSITION 2
POSITION 1
YELLOW BIOLOGICAL UNIT
DECLINOMETER
RECREATION AND REPLACEMENT UNIT
FINAL POSITION
STAND BY TO ABANDON HOPE
Mark I Birdometer

B



C

Figure 7-4. *A:* Experimental birdometer used during La Chalupa habitat program. *(Courtesy Marine Resources Development Foundation), Fort Lauderdale, Florida.)* *B:* Schematic Mark I birdometer. *C:* The world's first parrot aquanaut shown in Conshelf II. *(Photo courtesy of The Cousteau Society, Inc., 930 West 21st Street, Norfolk, VA 23517, a membership-supported environmental organization.)*

restricted to official business. Nevertheless, on one occasion the aquanauts persuaded the monitoring topside crew to play a game of bridge over the intercom system. The game lasted about 2 hours until it was detected by one of the program managers and halted.

The TV camera was an ever-present eye in many early habitat programs and was used for safety and/or medical and psychological monitoring. Although the aquanauts always were fully aware of the presence of the cameras, in some cases, the cameras were considered an invasion and were covered either to ensure privacy or as an act of hostility toward the surface. But usually the aquanauts adapted quickly and tended to ignore the cameras unless communicating with surface-support personnel. During Conshelf III, the monitors were sometimes referred to as "God"; less endearing names were assigned in other programs. It is not anticipated that monitoring will be necessary in the future except for special programs involving experimental studies of aquanauts or in situations in which seafloor marine studies require the use of TV.

Pets often played a role in entertaining the aquanauts. They came in many forms, ranging from a pair of frogs sent to the seafloor during Conshelf III, parrots in the same program, and a birdometer used during the La Chalupa program (Fig. 7-4). A sketch of this last device, referred to

as the XBM, also is shown in the figure. Operating instructions which were administered verbally were as follows:

> The XBM consists of a rod graduated in vols percent O_2 over a range of 0-21%. The rod is color coded for any desired end-point. The standard yellow biological analog (B.A.) will sound a musical, 3-note, sound from 21-18%; will silently and listlessly shuffle along the rod from 18-16%; and will fall off the rod, striking a chime, when oxygen drops to 15.25%. The XBM is maintained easily under field conditions with water and seed. Fathometer recording paper may be used beneath the XBM to keep the area under the B.A. clean. A second B.A. of the opposite sex will simplify the replacement problem during long live-ins.

Figure 7-4c shows Claude, the world's first undersea parrot, enjoying life in Conshelf II.

Pets also were included in at least one of the Soviet programs. In Ikhtiandr 1967, the aquanauts were accompanied in the habitat by a rabbit named Tishka, plus a few guinea pigs and rats. This managerie outlasted the aquanauts and remained on the seafloor in the habitat for 1 day after the completion of the mission.

In many habitat programs, pets were made of the local fish, and feeding these new-found friends was a source of constant pleasure, particularly when they came right into the entrance trunk to be fed. During a 1973 La Chalupa mission, for example, 2 large dog snappers were constant visitors, and aquanauts frequently had to push them out of the way when entering the water. In Sealab I, a large grouper inhaled a whole can of sardines from an unwary aquanaut. At times the ports literally were filled with fish observing the aquanauts, as shown in Fig. 5-9, and in other instances, an aquanaut whiled away some time fishing from inside the habitat, as is the Bulgarian aquanaut shown in Figure 7-5 during the Chernomor 1974 program.

In Link's 1964 Man-in-the-Sea program, the two aquanauts were awakened frequently during the night by resounding thuds against the walls of the inflatable SPID (Submerged Portable Inflatable Dwelling) habitat (Fig. 3-9). The cause of the thuds was a mystery until the aquanauts discovered that they were produced by large grouper pursuing of the swarms of small fish attracted by the light spilling from the port. Fish often would swarm around a habitat. In many programs, individuals or groups of fish would wait for the aquanauts to exit the habitat and follow them around looking for handouts.

The Hydrolab habitat lacked toilet facilities and required aquanauts to use the open sea for elimination. Local fish quickly learned to distinguish between fully suited aquanauts leaving the habitat for working purposes

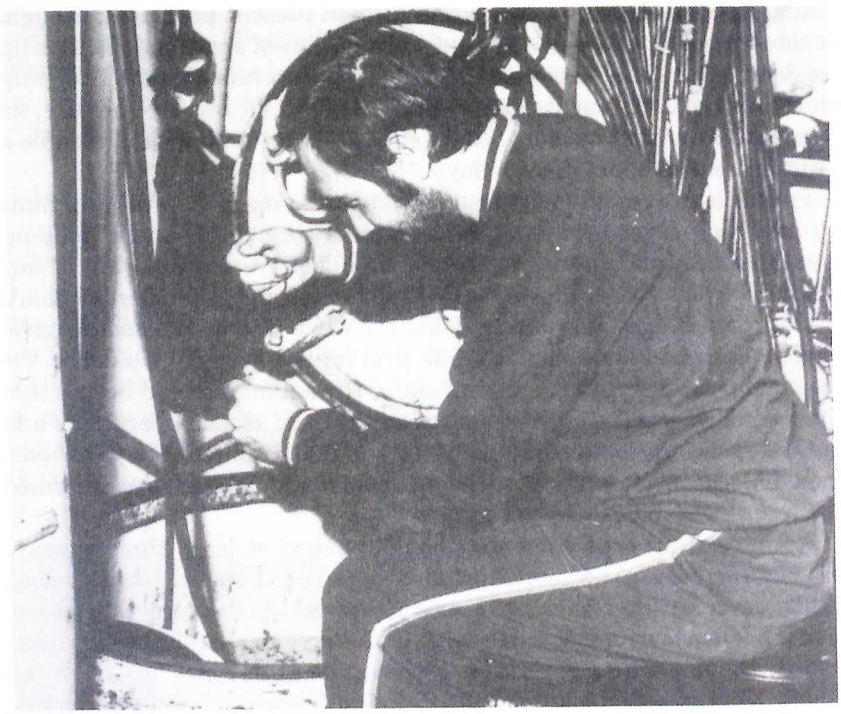


Figure 7-5. Bulgarian aquanaut fishing through entrance trunk during Chernomor '74. *(Courtesy of L. N. Klissurov, Institute of Oceanology, Varna, Bulgaria.)*

and skinny dippers with a tank under one arm answering nature's call. The fish quickly fell into formation behind the latter to perform their scavenger duties. More than once, aquanauts encountered an overzealous scavenger and got nipped on the derrier during a feeding frenzy.

Although these friendly and curious neighbors usually were fun to be around, there were a few occasions when their presence made the aquanauts take notice. One morning during a La Chalupa mission in which we participated, the aquanauts emerged to find a ring of about 100 barracuda circling the habitat. Finally the curiosity of the fish was satisfied, and they disappeared into the haze. During the FLARE program off the coast of Florida, two aquanauts swimming noticed a V-shaped formation of barracuda following the other. Neither aquanaut saw the group following himself, and each thought it better not to mention the crowd following the other until they were back inside the habitat.

Aquanauts often became protective of their fish friends, and even former spear fishermen would not consider spearing their "buddies."

Being part of an underwater aquarium could present problems, though, as the aquanauts of Sealab II found when hordes of scorpion fish took up residence around the habitat, especially in the entrance trunk. Stepping on one of these poisonous spined fish or grabbing one by mistake, as happened on a few occasions, could cause a painful sting and disable a diver for several hours or even days.

Precautions were taken against sharks during many habitat programs by providing cages around entrance trunks (Fig. 5-21) and equipping aquanauts with bang sticks and shark billies. We are unaware of any problems with sharks during a habitat program. An unusual shark problem arose, however, during Tektite I when one of the senior naval officers decided to have a shark bite drill on the surface. He called the base camp and informed them that one of the aquanauts had been bitten by a shark. His call triggered a planned series of rescue operations and got everyone up in the middle of the night. Unfortunately, no one, including the medical officer or the program manager, had been informed the rescue was a drill.

An interesting experience that has happened at least three times—twice during missions we participated in—is an earthquake on the seafloor. While never posing a threat, the experience was unnerving. The sensation is one of a low rumble, a quivering of the water, and a slight vibration. The earthquake we experienced occurred at dusk during a dive from La Chalupa about 400 to 500 feet (122 to 152 m) from the habitat. Our first thought was that the habitat had collapsed or shifted down slope. A quick swim back verified that this was not the case and that all was well. A radio check confirmed that an earthquake had been detected at the time noted by the aquanauts.

During Tektite II, earthquakes occurred during two of the missions, with similar reactions on the part of the aquanauts. One aquanaut described it thus: "as though I were trapped in a bowl of gelatin being shaken by a giant hand. My first thought was of an explosion within the habitat" (VanDerwalker, 1971, p. 285).

In general, daily life on the seafloor settled into a routine within 2 to 3 days. When the unexpected came to be expected, methods of handling the various crises became routine. Perhaps the spirit of adventure would have suffered had everything gone like clockwork.

SEAFLOOR CUISINE

Eating in the sea has ranged from a hastily made peanut butter sandwich to a gourmet meal. Although the importance of meals and mealtime behavior varied widely from habitat to habitat and crew to crew,

generally, breakfast and lunches were informal, quickly prepared, and consumed on an individual basis. The evening meal, on the other hand, often was the principal social event of the day, and the aquanauts looked forward to it (Fig. 7-6). Their reaction is consistent with meal behavior in other situations in which the environment is stressful and the work hard, such as on board ship and in polar wintering-over expeditions.

Where space and conditions permit, cooking with a microwave oven increases flexibility for quick but nourishing basic meals during the day when time is at a premium; use of the microwave also minimizes the heat and water vapor produced. Occasionally family members wanted to send down something special—perhaps an aquanaut's favorite dish or a birthday or anniversary cake. One wife during Sealab II discovered a fact of seafloor living when her angelfood birthday cake flattened to the thickness of a brownie because of the 200-foot (61 m) pressure in the habitat. Squashed angelfood cake points up the baking problem on the seafloor. Getting dough to rise is practically impossible. During Tektite II, one of



Figure 7-6. Enjoying supper in Sealab I. *(Official U.S. Navy photograph.)*

the aquanauts decided to surprise his comrades with a freshly baked chocolate cake. Even after using almost half a box of baking powder, the cake rose only briefly before settling into what could have been a model of a mushroom anchor.

Living off the sea was fairly commonplace. Many fish were devoured, though not the special friends of the aquanauts. In La Chalupa missions in which we participated, we had gourmet meals on several occasions when our Finnish aquanaut colleague decided to prepare flounder souffle. Broiled slipper lobster was a treat in other La Chalupa missions. During Sealab II, Chief Petty Officer Robert Sheats made more than one breakfast of a bowl of raw euphasid plankton. Sheats claimed it was excellent with cereal but left a strong after taste. Other Sealab II aquanauts found raw shrimp appealing. During Conshelf programs, aquanaut Laban also ate raw shrimp and attested that it was the ultimate in fresh seafood cocktail. A specialty during some of the Hydrolab missions was raw lobster and fish marinated in lemon and contraband vodka.

The LORA habitat used in Newfoundland under the ice (Fig. 9-14) was designed such that the distance between the bottom of the habitat and the seafloor was minimal. More than once the aquanauts ate so many raw mussels that the entrance trunk became blocked with their shells and had to be cleaned out before the aquanauts could enter the water. During the LORA program, because of the 28°F (−2.2°C) water surrounding the habitat, the fish were very lethargic and could be grabbed by hand. If the fish were then touched with a piece of ice, the supercooling would start a crystallization process and a fish-sickle was formed. The process could be reversed readily by placing the crystallized fish in a bucket of water where they returned to life and began swimming around.

In many of the tropical programs, scientists studying lobsters decided to conduct culinary experiments involving taste testing their subjects. Generally the reports were favorable, although frequently repeated experiments were required during the mission to see if the taste changed over a 2- to 3-week period. Conshelf III aquanauts were disappointed on one occasion when informed that lobster thermidor was not permissible because the sauce might be too difficult to digest.

Spicy foods were avoided in most habitats, as were foods with a reputation for causing gas. Still, an increased use of condiments, particularly salt and pepper, was reported, perhaps because of the decrease in taste sensitivity reported by aquanauts in several programs. Although in some cases the changes in taste may have been due to the fact that smoking was impossible, the causes for such changes are not clear.

Although standard beverages were consumed in most habitats—milk, coffee, fruit juices, and carbonated drinks—carbonated drinks were flat and tasteless because of the increased pressure in the habitat. One got the impression bubbles were going in rather that out when a can was opened.

Most habitats had rules against the use of alcoholic beverages on the seafloor, although many programs permitted wine with dinner. In Chernomor 1968, dry wine was prescribed for the aquanauts to increase their tone. (The Chernomor report did not clarify whether this referred to muscle or vocal tone.) A quote from Podrazhanskiy, Rostarchuk, and Stefanov (1973, p. 164) reflects the attitude of the Soviet aquanauts with respect to the wine prescription: "We drink the first and last toast for everything at once: for the underwater investigations, in order that this crew become the 'longest' in the world, for those who are in the sea, and finally, for all those who are supporting this experiment on the surface and on the shore."

The Soviet wine apparently was a surprise. A comment found in Podrazhanskiy reflects their astonishment: "It was a mystery for us how we came by the wine, avoiding the vigilant eye of the duty officer of the experiment and the physicians. However, we nevertheless asked for permission for our medicine before raising our glasses in congratulations." Such astonishment was experienced in many other habitat programs where wine, rum, beer, and other alcoholic beverages appeared suddenly and without warning. It was a continual source of amazement to program managers that such libations would appear in a habitat where all supplies were logged in and out and carefully inspected.

An interesting approach for obtaining liquor on the seafloor was used during the 1975 Helgoland program off the coast of Massachusetts. The aquanauts requested that a phone patch be made from the seafloor to a commercial liquor store in Gloucester. The connection was made and after determining that the store made deliveries, the aquanauts requested that a case of Black Horse Ale and a fifth of scotch be delivered to the habitat. The proprietor had to defer the delivery, but the order was waiting on shore when the aquanauts arrived following decompression.

During Tektite I, liquor delivery was made by the world's first underwater smuggler. In the middle of the night, a speeding boat would appear from nowhere, slow down as it passed the habitat site, and resume full speed before support boats could give chase. When the aquanauts heard the powerful boat coming, as arranged previously, they donned their equipment and bolted out of the habitat into the water to catch the case of rum. The case itself started to disintegrate about midwater and individual bottles began to fall. One aquanaut reported, "It was like trying to catch dollar bills fluttering through the air".

SOME CLOSE CALLS

The beauty and grace of living in the sea cannot be enjoyed without some peril. For many perhaps, the danger is part of the beauty. It is truly remarkable that to our best knowledge, 21 years of seafloor habitation

involving hundreds of aquanauts and support personnel has resulted in only two fatal accidents during habitat programs. The following accounts illustrate the resourcefulness, dedication, and strength of the men and women who took part in the first 21 years of seafloor exploration. The incidents reflect group and individual efforts to survive under the threat of impending disaster.

Conshelf II

It was May 13, 1963, and Cousteau's support ship *Calypso* was pulling out of Port Sudan towing Deep Cabin, a 20-foot (6.1 m) cylinder destined to be placed at a depth of 90 feet (27.4 m) as part of the Conshelf II program at Sha'ab Rumi Reef in the Red Sea (Fig. 3-7). Two men were to spend a week there on the seafloor. The ledge on which Deep Cabin was to be placed was too narrow for tripod legs, so a special cradle filled with lead bars was improvised to serve as an anchor.

While being lowered to the ledge on a nylon line, the cylinder tore loose from the moorings and slipped down the reef face. After it came to rest, it was hauled back into place with the help of a surface-based crane. But during the fall, a large number of electrical cables were pulled out. To avoid bringing the whole system back to the surface, which would delay the program a week, it was decided to repair the cables on the seafloor. The two electricians sent down to perform the work found the two lower rooms flooded, but the upper rooms where the repairs were to be done were dry. During the repairs, the habitat began to rock and once again slid down the reef, with the men trapped inside and the outside safety diver becoming entangled in his scuba harness. One of the men inside managed to escape through a lower hatch, only to see Deep Cabin plunging farther down with his friend trapped inside and the safety diver still entangled on the outside. The cylinder finally came to a rest precariously on a sand ledge at 140 feet (42.7 m) where the man trapped inside donned his scuba tank and waited in a pocket of air for rescue. The safety diver cut himself loose and made an emergency free ascent from the 140 foot (42.7 m) depth. The electrician who had escaped from Deep Cabin ascended safely to the surface and reported what he'd seen. Two divers from the surface then descended to the habitat and extricated the trapped electrician. All returned safely to the surface.

Deep Cabin subsequently was returned to the 90-foot (27.4 m) ledge and the one-week mission carried out as planned (Cousteau 1964).

Sealab I

On the eighth day of Sealab I (July 27, 1964), the aquanauts were participating as photographers in an operation involving the one-man

submersible STAR I. They were about 70 feet (21.3 m) from the habitat, which was resting on the seafloor at a depth of 193 feet (58.8 m). One of the aquanauts, wearing a navy MK VI semiclosed circuit scuba system, had to return to the habitat for film. But as he was leaving the habitat, he struck his gas-control yoke on the structure and forced it closed, which prevented him from getting oxygen from the inhalation bag. After about five minutes, he realized something was wrong and made a dash for the habitat. At the entrance trunk, he lost consciousness and floated into the opening where, by chance, his tanks struck the hull. This noise alerted the aquanaut on watch inside who came to investigate and found his friend drifting toward the aft end of the shark cage. He jumped in and raised the unconscious aquanaut's head above water and signaled for help from the other aquanauts. Between them they revived the unconscious man and got him into the habitat.

This was a case of a near-fatal incident caused by neither diver error nor equipment failure in which a death was prevented by the alertness and prompt action of a well-trained and experienced diver. The victim suffered no injury or residual damage.

Sealab II

A constant concern of aquanauts is the threat of accidental surfacing once saturated. The medical support team of Sealab II estimated that an aquanaut ascending from the 205-foot (62.5 m) saturation depth probably would be unconscious before reaching the surface. While on a dive, one of the aquanauts using the navy MK VI semiclosed diving system suddenly found his bypass was free-flowing, causing one side of the vest bag to inflate and resulting in the beginning of a rapid ascent. The aquanaut was not thoroughly familiar with the diving gear and did not react properly. He swam for what seemed an interminable time, fighting the buoyancy, until he managed to make it to the bottom and grab a stake. His buddy subsequently assisted him back to the habitat. A few seconds more and the aquanaut would have drifted to the surface, with little hope of rescue.

A similar incident occurred when one of the aquanauts decided to transfer some of his personal belongings to the transfer pot drop area. He put them into a large plastic bag and proceeded to swim toward the pot without putting on any of his diving equipment. The plastic bag became so buoyant that it started dragging him toward the surface. He managed to grab the shark cage and pull himself back into the habitat.

Chernomor

On July 20, 1968, the Chernomor habitat with its crew of four aquanauts was resting on the floor of the Black Sea at a depth of 49.9 feet (15.2

m) during a test dive. About 5:00 A.M. the crew was awakened by a series of blows and jolts. A sudden storm had created a sea turbulent enough to lift the habitat off the seafloor and smash it down again and again. By 6:00 A.M. the jolting caused a list of up to 30°. To add to their problems, the aquanauts found that the ladder used for entering the habitat had been left in place the night before, prior to closing the hatch, and was being forced against the hatch with every drop, threatening to force it open. While being shaken like dice in a box, the aquanauts finally managed to open the hatch and pull the ladder inside.

By this time the shore-support team had been alerted and plans activated to retrieve the aquanauts if necessary. Seas now were almost 10 feet (3 m) on the surface, and plans were underway to bring the habitat up. The Chernomor habitat was designed for the aquanauts to decompress inside; at the depth of 49.9 feet (15.2 m), the scheduled decompression time was 10 hours. Following repair of a valve damaged by the jolting, decompression was begun in a habitat in which it was difficult to stand. By midday, waves had reached a height of over 13 feet (4 m), and the aquanauts were requested to plan an emergency evacuation.

A ship containing a recompression chamber had been dispatched to the dive site for this eventuality. By now the prow supports had been torn from the habitat, and it was being smashed even more violently against the bottom. At about 3:00 P.M., with about 4 hours of decompression remaining, a decision was made to bring the habitat to the surface. This was accomplished under extraordinarily difficult conditions; all four aquanauts were transferred into a single place recompression chamber and recompressed to a pressure of 1.5 ATA. On reaching shore, the aquanauts were transferred to a larger decompression chamber, where they completed their decompression at 9:00 P.M. (Podrazhanskiy, Rostarchuk, and Stefanov, 1973).

The Chernomor program was plagued with similar problems through 1972. The difficulty always was the same—insufficient ballast and bad weather. The first scientific mission in August 1968 also was aborted after 5 days due to the tossing about of the habitat on the seafloor. The diaries of some of the aquanauts indicate that the buffeting was so severe they had trouble staying in their bunks. In this mission, the habitat was surfaced, and the aquanauts transferred to a shore-based decompression chamber in the same manner as during the test dive just described.

On July 12, 1969, the habitat, at a depth of 39.4 feet (12 m), was again thrown about and smashed against the bottom, this time by a cyclone. The crew of four began decompression inside while being tossed about and again surfaced in the habitat and completed decompression in a shore chamber.

Perhaps the most dangerous situation for the Chernomor crew occurred

on September 20, 1971. A severe storm caused the habitat, located at a depth of 49.2 feet (15 m), and the support buoy to drift shoreward with the crew inside, still under pressure. All communication between shore and habitat was severed as the habitat was washed up onto the shoals in the surf zone. The situation is best described by a quotation from the diary of aquanaut N. Ye. Denisov:

> Impacts against the bottom were renewed. They even became more frequent. The waves began to tumble over the port side. Lasha crept under the table. Vlada tumbled with the mattresses. Igor was at the very bottom against the wall, sitting on the floor, and I hung in my rubber straps, like a toy clown. While we thought, three clear impacts were heard. Our joy is difficult to describe. We found that we were at the surface! This was also confirmed by the voice of Volodya Davidovich, heard by us through the hull. I immediately became calm. [Podrazhanskiy, Rostarchuk, and Stefanov, 1973, p. 165]

The five aquanauts climbed out of the habitat onto the steep shore and up to a road. A waiting car hustled them off to the shore decompression chamber, where within 10 minutes they were recompressed to a depth of 98.4 feet (30 m) and subsequently decompressed.

Remarkably, in this series of mishaps and near misses involving the Chernomor habitat, no lives were lost, and the habitat managed to remain intact in spite of the damage it suffered. The crews of these programs enjoyed periods of enraptured tranquility interspersed with periods of sheer terror.

Helgoland

The Helgoland mission referred to as Lubeck II in the Baltic Sea took place in July 1976. The four-man crew consisted of one German and three Americans. Saturation depth was 40 feet (12.2 m). On July 18, the crew, annoyed with noisy deck plates inside the habitat, decided to fix them. One of the crew began applying trichloroethylene (plastic model) glue to the rubber strippings on the bilge framework in the main room at about 10:00 A.M. They noticed no fumes or ill effects. By 5:00 P.M., however, one of the aquanauts experienced undue fatigue, and another found he was having trouble in the routine task of sorting specimens. By 9:00 or 10:00 P.M. two aquanauts had gone to bed. The other two stayed up talking until about 2:00 A.M. By this time they were experiencing problems of balance, speech, and appeared to be drunk. All aquanauts awoke by 10:00 A.M. (at least 2 to 3 hours later than usual), and one suited up for the first dive of the day. Immediately after entering the

water, he returned to the main room, sat down, vomited, and said he had to go lie down. He was given oxygen and clean compressed air, and the physician on the surface was notified. The habitat was vented two or three times, a process that used all the reserve compressed air, and the physician swam down to examine all aquanauts at 1:00 P.M., 27 hours after the glue had been used. All diving was cancelled until the next morning when the life-support monitoring system indicated the atmosphere was once again safe. When discussing the situation later, the aquanauts realized that their reason for delay in notifying the physician on the surface was they all were in a state of drunken euphoria.

This glue-sniffing episode could have had disastrous consequences for the entire crew if prompt action had not been taken once the surface support was notified. The experience clearly illustrates the thin line between a safe environment and a dangerous situation. Using the glue was in violation of habitat rules; the glue, in fact, should not have been in the habitat. It had been used for repairing wet suits, where the small amount required was not a problem. There were no residual effects for any of the aquanauts.

La Chalupa



In April 1973, the La Chalupa habitat was deployed for a 100-foot (30.5 m) mission about 10 miles (16 km) off the southwest corner of Puerto Rico. La Chalupa was supported on the surface by an unmanned buoy, which meant that help was 10 miles away on shore. The problem occurred on the second day of a 2-week mission. Only three aquanauts were in the habitat because the fourth had become ill just before the descent and was to join them the following day.

All three aquanauts were in the water. One (author Miller), using the hookah, was preparing some experiments about 20 feet (6.1 m) from the habitat. The other two were laying out transect lines for experimental and navigational purposes. One of these two aquanauts (author Koblick) was wearing a closed-cycle rebreather in place of conventional scuba. The rebreather had been checked out thoroughly in the habitat, in the water of the entrance trunk, and by swimming around the outside of the habitat for more than half an hour. At a distance of about 500 feet (152 m) from the habitat, the aquanaut wearing the rebreather began to get short of breath and knew something was wrong. He quickly headed back to the habitat, assisting himself by pulling along the transect just laid. The second aquanaut followed. On reaching the entrance trunk, the stricken aquanaut lost consciousness and sank to the bottom under the trunk, losing his mouthpiece in the process. The second aquanaut, although exhausted himself, managed to pull his unconscious buddy from the

bottom and raise his head out of the water but did not have the strength to lift him into the habitat. By chance, the third aquanaut returned to the habitat at this moment to get a tool. They pulled the unconscious aquanaut into the habitat, where they determined he was still breathing. Once the situation was stabilized and the stricken aquanaut again breathing regularly, the surface-support station was notified. The aquanaut was put to bed, and care was administered in accordance with the instructions from the topside physician. The next morning, the physician visited the habitat to examine the aquanaut and found no residual damage. The problem with the rebreather turned out to be a malfunction in the CO_2 scrubber system; the aquanaut had experienced a severe CO_2 buildup. A tragedy was averted here because of the aquanaut's strong will to survive. His retrieval from the water was greatly facilitated by easy access to the habitat, which had no long ladder to climb or narrow trunk to navigate.

A year later (May 1974) the authors and two other aquanauts were conducting a mission to test some newly developed descending excursion diving procedures. Once again the habitat was 10 miles (16 km) off the coast of Puerto Rico at a depth of 100 feet (30.5 m). All the test dives were made using a 700-foot (213 m) long air (hookah) hose attached to the habitat. During one of the test dives to a depth of 250 feet (76.2 m), the author (Miller) had to ditch the commercial lightweight helmet (KMB-8) being used because a faulty hose connection caused the hookah hose to separate. The return to the habitat was made using a standard regulator and twin scuba tanks carried for just such an emergency. In this instance, the ditching was accomplished smoothly because the aquanaut had spent several hours practicing the helmet ditching procedure prior to the mission.

Hydrolab

In November 1972 a series of problems occurred. Four aquanauts were in Hydrolab at a depth of 42 feet (12.8 m), just a mile off the shores of Grand Bahama Island. On the second day of the mission, one of the aquanauts was given chlorpheniramine for a sinus problem. This normally mild antihistamine resulted in the aquanaut's becoming "drunk" in about ten minutes and being in a semiconscious state for the next 24 hours. Although he recovered fully, he made no more dives the remainder of the mission. Another aquanaut, also on the second day of the mission, started taking medication for an ear infection. The next day he fainted while coming into the habitat through the entrance trunk. He made only one more dive during the 4-day mission. These two cases demonstrate clearly that we know little of the effects of common drugs when they are taken in a hyperbaric environment.

The problems on this mission continued. During the 15 hour and 30

minute decompression to the surface, the oxygen supply ran out, and extra oxygen had to be brought from shore, a process that extended decompression and added oxygen time. The final problem associated with this ill fated mission occurred when the two aquanauts who had been sick in the habitat developed pains during the 35-minute flight back to the mainland from Grand Bahama. These pains developed despite the required 30-hour interval between completion of decompression and departure, plus the fact that the aircraft captain stated that the the cabin pressure was maintained at about sea level. These symptoms dissipated and did not require treatment. The other two aquanauts reported later that they also felt poorly for several days after the mission. After this, all Hydrolab aquanauts were required to wait 48 hours between completion of decompression and the flight to the mainland. In addition, all drugs were logged in by the operations director and approved by a physician prior to beginning the missions.

Another close call involving Hydrolab took place during Project SCORE (Scientific Cooperative Operational Research Expedition), which began on April 1, 1975, off the coast of Freeport, Grand Bahama Island. The project was designed to conduct excursion dives to depths as great as 250 feet (76.2 m) from the Hydrolab habitat located at a depth of 50 feet (15.2 m).

On the first day of the operation, a team of divers headed for the experimental site over the submerged cliff (Fig. 4-18). Both divers wore closed cycle rebreathers and were accompanied by a safety diver wearing standard scuba equipment. During the descent, one of the aquanauts was observed to be having trouble clearing his ears and was seen to be checking the oxygen readouts on his rebreather frequently. When they reached a depth of about 140 feet (42.7 m), the two aquanauts started swimming back up-slope. The safety diver swam in front of the aquanaut, who seemed to be having trouble, and gave him the OK signal. There was no response. The aquanaut stared straight ahead, breathing rapidly and deeply. The safety diver motioned him to go to one of the safety stations about 150 feet (45.7 m) away at a depth of 90 feet (27.4 m). The stricken aquanaut suddenly spat out his mouthpiece and clenched his mouth so tightly that he could not take the mouthpiece of the safety diver. A few seconds later, he threw up his hands, pulled off his mask, and started making convulsive motions. The safety diver and the other aquanaut were able to get the stricken aquanaut to the safety station in about a minute. The victim had stopped breathing by this time, and the safety diver administered mouth-to-mouth resuscitation. The aquanaut began breathing again but went into convulsions so violent it took both of the other men to hold him down. After about 30 minutes, the victim was stabilized, sitting up and talking. He subsequently was transferred to the

lockout compartment of the Johnson Sea-Link submersible (Fig. 4-18) with the aid of a full helmet, then to the surface, and back to the mainland where he recovered completely. The rebreather unit was examined thoroughly by experts following this incident and found to be in good operating condition. A fatality was avoided by prompt action of the safety diver. Apparently the problem occurred because the victim was inexperienced in using the rebreathing equipment.

Getting Lost

A number of incidents have occurred over the years in which aquanauts have become lost from the habitat. In Sealab II, off the coast of La Jolla, California, two divers became temporarily lost at a depth of about 250 feet (76.2 m) a short distance from the habitat. Because of the almost zero visibility, they were supposed to hold onto lines leading back to the habitat while doing their work. But they became engrossed in their work and forgot the lines. After five minutes of groping in the mud, they relocated the lines leading to safety.

During the FLARE program in 1972 (Fig. 6-12), two aquanauts were swimming along a reef face conducting marine science investigations. Return to the habitat required keeping the reef on their right. Because there was a gap in the reef, the aquanauts swam around a corner and ended up some distance from the habitat and totally lost. They were forced to ascend as far as was safe to survey the seafloor and regain their bearings. The problem here was not the depth because the saturation was only 45 feet (13.7 m); it was one of running out of air. They found the habitat just as their air ran out.

A similar problem was encountered during the Helgoland program in the Baltic Sea in 1974 where two aquanauts became lost in spite of an elaborate grid work on the seafloor. They made a wrong turn and then followed the grid lines in a large circle around the habitat instead of heading directly for it. The saturation depth was 70 feet (21.3 m), and the consequences could have been serious.

FATAL ACCIDENTS

During twenty-one years of seafloor habitat operation, we know of only two accidents resulting in the death of aquanauts. The first occurred in February, 1969 off the coast of San Clemente Island, California, during the final stages of preparation for the U.S. Navy Sealab III program. The victim was Barry Cannon, an experienced civilian diver with the navy and a veteran of Sealab II in 1965. While attempting to open the habitat

at a depth of 600 feet (182.9 m) for the start of the first mission, a malfunction occurred in Barry's breathing equipment. The resultant CO_2 buildup caused death by asphyxiation in minutes despite heroic efforts by his buddy diver to rescue him. An investigation revealed that CO_2 absorbent material had not been placed in the scrubber canister. This incident plus related programmatic decisions signaled the end of Sealab III and the end of the U.S. Navy's Man-in-the-Sea program.

The second fatal accident occurred on September 25, 1975, in the Gulf of Maine off the coast of Rockport, Massachusetts. The German habitat, Helgoland, was in place on the seafloor at a depth of 111.5 feet (34 m) for a series of scientific missions. The habitat had been occupied for two days by three German divers and two U.S. divers for purposes of checking out the system. On completing the checkout, they underwent a 49-hour decompression inside the habitat. The divers were scheduled to surface on completion of decompression but because of bad weather, heavy seas, and a desire to have them surface during daylight, there was a 15½-hour delay before the ascent began during which the aquanauts remained inside the habitat. While returning to the surface the following day (September 25), Joachim Wendler, one of the German divers, suffered a fatal massive gas embolism in the final 15 feet (4.6 m). A board of investigation appointed by the NOAA concluded that the tragedy was in no way connected with the habitat systems or decompression procedures used (National Oceanic and Atmospheric Administration, 1977). As a result of this investigation, it was decided to continue with the program.

A third fatal accident occurring during a habitat program, but not involving an aquanaut took place at the beginning of the BAH-I program in the Baltic in September 1968. The victim was Dr. Horst Hartmann, scheduled to be the medical director for the program. Dr. Hartmann died during a reconnaissance dive without ever having entered the habitat.



INTROSPECTION

The lure and fascination of the sea have been described by some of the world's most cherished authors. Living within the sea, however, introduces an entirely new dimension. There is a surprisingly rapid change from being an alien visitor in another world to becoming an integral part of it. The feeling of being an interloper fades and is replaced with a sense of belonging—to the extent that visitors to habitats from the surface often were viewed as the interlopers and welcomed with mixed feelings.

The team on the seafloor evolves into a minisociety with its own rules, mores, and instant traditions born of a common experience. Even with the sometimes overwhelming problems of equipment malfunctions, dangers,

and difficulties of simple living, a routine develops that may or not include those on the surface. Although the support teams are working equally hard to ensure a successful mission, for some aquanauts the surface was totally replaced by the world around them. Gazing out the ports, especially at night, is a unique experience; to swim out of a home in the sea by moonlight and watch ethereal shapes passing all around is unforgettable.

For us, one of the truly indelible experiences occurred during the second mission in the La Chalupa habitat. Excursions lasting up to 4 hours were required to test for nitrogen narcosis at depths down to 250 feet (76.2 m). These excursions, made with hookah, included a hard wire communication system for administering tests of mental alertness. Between tests, the aquanauts in the habitat played stereo music over the communications system. The experience of hanging over an undersea cliff in deep blue water for hours watching fish, the ebb and flow of water, swaying of soft coral and sea plants, while listing to beautiful music will never be forgotten.

The desire to stay longer on the seafloor, while common among aquanauts, was not unanimous. Near the end of a 2-week mission, one of the Bulgarian aquanauts was asked, "What is your greatest wish?" "To look at the stars as you can, to feel the wind blowing, and to pace back and forth on the deck. And one other thing; a taste of good wine," he answered (Uvaliev, 1973).

By contrast, at the end of a 15-day mission in Sealab II, postdive interviews elicited the following comment from an aquanaut:

> I thought I was going to miss the sun, the clouds . . . and I didn't miss the sun once, nor the clouds, nor the sky. Because it was another world. It was topside. We had our world down there. Our daylight started around 8:00 A.M. and ended around 3:30 P.M. We adjusted very, very rapidly to that. And our nights were much more beautiful than yours. We had much more to see, and we became very, very self-centered. I think I liked it down there just as well as up here for a short period. When those guys came down there for the third team, I thought they were intruding. I hated to see them come in because I realized that was the end.

The feeling left behind after living in the sea was stated simply yet eloquently by Albert Falco following his 1 week in Conshelf I: "I don't know exactly what has happened. I am the same person, yet I am no longer the same. Under the sea everything is —"; he paused to be sure of what he wanted to say; "Under the sea, everything is moral" (Cousteau, 1964b, p. 239).

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Chapter 8

Saturation Excursion Diving Experiments and Procedures: A Review

A recurring theme throughout the preceding chapters is the advantage of the virtually unlimited bottom time offered by seafloor habitats. At present there is no evidence to suggest a limitation on the length of time that humans can live under pressure on the seafloor if the proper life-support system is provided. Experience gained from habitat programs to date has shown that the amount of time spent in the water by aquanauts is limited by fatigue, cold, and equipment rather than by basic physiological or anatomical restrictions. Thus, there appear to be no technical or physiological reasons why aquanauts could not remain in the sea for months or even years at a time without returning to the surface.

If the potential of seafloor habitats is to be realized, aquanauts need the capability to move about freely in the water column. Whereas mobility in the horizontal plane is limited only by life-support and propulsion equipment when the depth of the dive does not vary significantly from the depth of the habitat, mobility in the vertical dimension is subject to physiological limitations.

Historically aquanauts have been limited to relatively narrow vertical excursion ranges either because of a flat local topography in the vicinity of the habitat or by operational rules established in the absence of information on safe vertical excursion procedures. For example in the U.S. Navy's Sealab II program, aquanauts were prohibited from ascend-

ing or descending more than 33 feet (10.1 m) above or below the 205-foot (62.5 m) saturation depth (Pauli and Clapper, 1967). Aquanauts of Conshelf I, who were saturated at a depth of 35 feet (10.7 m), were permitted to ascend and descend to depths of 15 feet (4.6 m) and 80 feet (24.4 m), respectively. In Conshelf III, ascending and descending excursions were limited to depths of 295 feet and 410 feet (90 and 125m), respectively, from the 328-foot (100 m) depth. In Tektite, where the saturation depth was 42 feet (12.8 m), vertical excursions were allowed up to a depth of 25 feet (6.1 m) and down to a depth of 100 feet (30.5 m).

Standard diving tables are based on the assumption that the diver is saturated on air at 1 atmosphere and that all diving will be done by departing from and returning to the surface. When diving is done either at high altitudes where atmospheric pressure is reduced or from seafloor habitats where pressure is increased, the surface-based tables are not applicable without some modification. If the surface tables are used without being modified, the high-altitude diver is not protected adequately, and the aquanaut diving from a seafloor habitat is unduly restricted.

Boyle's Law states that the volume of a parcel of gas is inversely proportional to its pressure and that a change in volume is a function of the relative change in pressure. A conservative interpretation of Boyle's Law is that an excursion to a deeper depth, when saturated at depths greater than 1 atmosphere, can be conducted safely using a conventional diving table on a differential basis. Thus, an aquanaut saturated at a depth of 100 feet (30.5 m) could descend to a depth of 180 feet (54.9 m) for the same period of time as he or she could when diving to 80 feet (24.4 m) from the surface.

There are considerable data now available, however, showing that saturated aquanauts making vertical excursions do not have to adhere to the same excursion times imposed when diving from the surface.

Because of the importance of maximizing vertical mobility when using an undersea habitat, a review of the principal laboratory and field studies involving vertical excursions from a saturated condition is included here. The review is limited to studies and programs in which the breathing mixture was either air or nitrogen-oxygen. Excursion diving procedures involving helium breathing mixtures are well documented and either have been reported elsewhere (Bornmann, 1971; Spaur et al., 1976; U.S. Navy Diving Manual 1979) or are unpublished because of commercial proprietary interests.

Two terms need defining to ensure that readers will understand the studies discussed in this chapter. The first is *partial pressure.* In a mixture of gases, the proportion of the total pressure contributed by a single gas in the mixture is called the partial pressure. The partial pressure contributed by a single gas is in direct proportion to its percent-

age of the total volume in the mixture. Thus, as stated by Dalton's Law, "The total pressure exerted by a mixture of gases is the sum of the pressures that would be exerted by each of the gases if it alone were present and occupied the total volume."

The second term is *normoxic breathing mixture.* A normoxic (normal oxygen) mixture is one in which the partial pressure of oxygen at a specified depth is close to or slightly above the normal (surface) atmospheric value of 0.21 (21%). As the depth increases, the amount of oxygen in a normoxic breathing gas is decreased by the amount necessary to maintain the desired partial pressure. Let's assume that a saturation dive to 100 feet (30.5 m) is planned, and it is desired to maintain a normoxic breathing mixture with a partial pressure of oxygen of 0.21. The total pressure at 100 feet is 4.02 atmospheres absolute (ATA) (1 atmosphere at the surface plus 3 atmospheres of water). What will be the percentage of oxygen in the breathing gas?
Referring to Dalton's Law we see that:

% of the component × total pressure (absolute) = partial pressure.

In our example:

% oxygen × 4.02 (total pressure) = 0.21 (desired partial pressure).

Converting the formula,

$$\%\text{oxygen} = \frac{0.21}{4.02}$$

% oxygen at 100 feet = 0.05 (5%).

A given breathing mixture may be achieved by adding nitrogen or helium to air or by allowing the initial habitat air to be breathed down by the aquanauts until the desired partial pressure is reached.

FIRST EXCURSION DIVING STUDY

Larson and Mazzone (1967) reported on the first experimental program designed specifically to study vertical excursion diving from air saturation. The diving tables were developed by Robert D. Workman and were based on a method he had derived earlier (Workman, 1965). The bottom times were preselected, and the allowable maximum depths were calculated based on no-decompression dives.

Compressed air was used as the breathing gas for the 35-foot (10.7 m)

saturation exposures, the excursions, and during decompression. The dives were made first using large dogs and then repeated with human subjects. All excursions were made after a 24-hour period of saturation. Although many repetitive excursions were made with the animal subjects during a single saturation exposure, only one excursion per saturation was made by the human subjects except in the first saturation. In this instance, two excursions were made to 165 feet (50.3 m) for 30 minutes with a 4-hour interval back at the 35-foot (10.7 m) saturation depth between excursions.

Table 8-1 presents a summary of the animal and human excursion depths and times. It shows that all excursions were made successfully without any cases of decompression sickness. If these bottom times are compared with allowable bottom times when diving from the surface (U.S. Navy Diving Manual, 1979), the advantages of starting such dives from a saturation depth of 35 feet (10.7 m) are apparent. Table 8-2 shows the net depth (depth below the saturation level) of the excursion, and Table 8-3 shows the bottom times compared to the times allowed from the surface. For example, in Table 8-2, a dive to 130 feet (39.6 m) from the surface permits a bottom time of 10 minutes, whereas one can make a dive to a depth of 165 feet (50.3 m) from 35 feet (10.7 m), a net depth of 130 feet, and stay for 30 minutes. The advantage is even more apparent where it is seen in Table 8-3 that one can remain at 165 feet (50.3 m) for 30 minutes when saturated at 35 feet (10.7 m) as compared to 5 minutes from the surface.

Table 8-1. Animal and Human Excursion Dives While Saturated on Air at a Depth of 35 Feet of Seawater (fsw)

Excursion Depth		*Excursion Time*	*Number of Excursions*	
(ft)	*(m)*	*(min)*	*Animal*	*Human*
165	50.3	30	13	6
135	41.2	60	8	4
117	35.7	90	4	1
109	33.2	120	4	2
105	32.0	150	4	2
100	30.1	240	3	2
Total			36	17

Source: After R. Larson and W. Mazzone, 1967, Excursion Diving from Saturation Exposures at Depth, in *Proceedings of the Third Symposium on Underwater Physiology,* March 23-25, 1966, Washington, D. C., C. Lambertsen, ed., Williams & Wilkins, Baltimore, p. 244; copyright © 1967 by The Williams & Wilkins Co.

Table 8-2. Allowable Bottom Times for Various Net Excursion Depths

Net Depth		*From Surface*	*From 35 Feet*
(ft)	*(m)*	*(min)*	*(min)*
130	39.6	10	30
100	30.5	25	60
82	25.0	38	90
74	22.6	46	120
70	21.3	50	150
65	19.8	55	240

Source: After R. Larson and W. Mazzone, 1967, Excursion Diving from Saturation Exposures at Depth, in *Proceedings of the Third Symposium on Underwater Physiology,* March 23–25, 1966, Washington, D.C., C. Lambertsen, ed., Williams & Wilkins, Baltimore, p. 248; copyright © 1967 by The Williams & Wilkins Co.

Table 8-3. Allowable Bottom Times for Various Total Depths

Net Depth		*From Surface*	*From 35 Feet*
(ft)	*(m)*	*(min)*	*(min)*
165	50.3	5	30
135	41.2	10	60
117	35.7	17	90
109	33.2	20	120
105	32.0	22	150
100	30.5	25	240

Source: After R. Larson and W. Mazzone, 1967, Excursion Diving from Saturation Exposures at Depth, in *Proceedings of the Third Symposium on Underwater Physiology,* March 23–25, 1966, Washington, D.C., C. Lambertsen, ed., Williams & Wilkins, Baltimore, p. 249; copyright © 1967 by The Williams & Wilkins Co.

TEKTITE LABORATORY STUDIES

A constant concern of saturated aquanauts is inadvertent or accidental surfacing. In an effort to learn how to cope with such an emergency, a study was conducted in 1968 in preparation for Tektite I to determine the safe surface interval between direct surfacing from a 42-foot (12.8 m) saturation depth (on a normoxic breathing mixture) and the onset of decompression sickness (Edel, 1971*b*). In other words, what was the safe ascending excursion time limit from 42 feet (12.8 m) to the surface? This study, carried out in the chamber facilities of J and J Marine, Houston, Texas, also was designed to develop treatment tables to be used in the event of bends following accidental surfacing.

Six subjects were saturated in a normoxic atmosphere at 42 feet (12.8 m). All six were decompressed to the surface in 1 minute. Two subjects each remained at the surface for 10, 15, and 20 minutes prior to recompression to 42 feet (12.8 m). No symptoms were noted for the 10- or 15-minute groups. One subject in the 20-minute group developed serious neurocirculatory symptoms after 19 minutes, which dissipated rapidly on recompression to 60 feet (18.3 m). Based on these experiments, "A surface interval of 15 minutes after accidental surfacing before recompression to 60 feet (18.3 m) was accepted as safe against the liability of dysbarism" (Beckman and Smith, 1972, p. 160).

In anticipation of using the Minitat habitat at a depth of 100 feet (30.5 m), the Tektite program included laboratory studies of vertical excursions from a normoxic nitrogen-oxygen saturation at 103 feet (30.5 m). Two subjects each were used in ascending and descending excursion experiments, again at J and J Marine. In the descending excursion tests, the subjects spent 6 hours at 175 feet (53.4 m) breathing air, followed by a 3-minute ascent back to the 103-foot (31.4 m) saturation depth, with no symptoms of bends noted (Edel, 1969). In the ascending excursion tests, the subjects ascended from 100 feet (30.5 m) to 70 feet (21.3 m). One subject spent 8 hours at 70 feet breathing air for the first 4 hours while doing weight-lifting exercises. This was followed by 4 hours of rest breathing a mixture of 90% nitrogen and 10% oxygen. The other subject spent 4 hours at 70 feet breathing the same nitrogen-oxygen mixture while performing physical exercise (Edel, 1971a). Both subjects returned to the saturation depth of 103 feet (31.4 m) without incident.

Based on these studies, the Tektite Medical Board agreed to allow ascending excursions from 100 feet (30.5 m) to 75 feet (22.9 m) for 4 hours and descending excursions to 175 feet (53.4 m) for 4 hours, with a 12-hour interval between any descending excursion and an ascent to 75 feet (22.9 m) (Beckman and Smith, 1972). By comparison, the time limits for excursions up to 25 and down to 100 feet (7.6 to 30.5 m) used during the 42-foot (12.8 m) Tektite II program were 4 hours. While several upward excursions to 25 feet (7.6 m) were made, the seafloor topography did not permit downward excursions beyond a depth of 65 feet (19.8 m).



SOVIET CHERNOMOR STUDIES

From 1970 to 1972, a series of experiments was conducted in the Soviet Union as part of the Chernomor program to develop profiles for excursion diving (Grinevich, 1975*a*). According to Grinevich, saturation depths and excursion profiles were calculated based on the previous work of Holden and Priestley (1937). The basic assumption was that the satura-

tion depth becomes a new surface and that descending excursions can be made on the same basis as from the real surface (1 ATA).

The work was carried out in a hyperbaric chamber, designated a PDK-3, that was equipped for extended saturation diving. Four teams of three men each were saturated at depths of 32.8, 65.6, 98.4, and 131.2 feet (10, 20, 30, and 40 m). Extensive biomedical studies were conducted before, during, and after each saturation exposure. A nitrogen-oxygen breathing mixture was used at the saturation storage depth. Excursions were completed using nitrogen-oxygen to depths up to 196.8 feet (60 m), with deeper excursions made using a mixture of 50% air and 50% helium (Table 8-4).

Eighteen no-decompression man-excursions were carried out from a saturated depth of 32.8 feet (10 m) without any signs of decompression sickness. One excursion was made each day. Return to the saturation depth was at the rate of 65.6 feet per min (20 m per min).

From a saturation depth of 65.6 feet (20 m), a total of forty-two man-excursions were made during a 15-day saturation program in the PDK-2 chamber. The breathing gas at the storage depth was an 88.5-10% nitrogen-oxygen mixture. (The discrepancy in the percentages was in the original translation). The same breathing mixture was used for excursions up to 196.8 feet (60 m). Twenty-one no-decompression descending excursions were made. Ascending excursions also were made, and in one instance, two divers ascended to the surface (1 ATA) where they stayed for 2 or 3 minutes before returning to the saturation depth. During this

Table 8-4. Excursion Times (min) for Chernomor Laboratory Experiments

Saturation Depth		*Excursion Depth*										
(ft)	*(m)*	*Ft* / *M*	*65.6* / *20*	*98.4* / *30*	*131.2* / *40*	*164* / *50*	*196.8* / *60*	*229.6* / *70*	*262.4* / *80*	*295.2* / *90*	*328* / *100*	*360.8* / *110*
32.8	10		240	45	25	15	10	8	6			
65.6	20			240	45	25	15	10	8	6		
98.4	30				240	45	25	15	10	8	6	
131.2	40					240	45	25	15	10	8	6

Note: Excursions in shaded area were made using a 50/50% air-helium breathing mixture. All other excursions were made using the same nitrogen-oxygen breathing mixture on which the divers were saturated.

Source: Data from V. Grinevich, 1976, Results of a Series of Experimental Studies in Shore-Based Hyperbaric Complex, and Use of Nitrogen at Moderate Depths during Long-Term Stay of Man under Water, in *Undersea Medical and Physiological Investigations,* A. Kolchinskaya, S. Gurevich, S. Gulyar, V. Bratus, V. Grinevich, B. Shaparenko, V. Nikolayev, F. Serkov, and A. Monin, translation TT-F-16883, National Aeronautics and Space Administration, Washington, D. C., pp. 172-180, 201-205.

excursion, one diver experienced a small pain in a finger of the right hand after 3 minutes (Grinevich, 1975a); the pain disappeared within 2 or 3 minutes upon recompression to 65.6 feet (20 m). It was concluded that an aquanaut can remain safely at the surface for 3 minutes when ascending from a saturation depth of 65.6 feet (20 m).

On another occasion, two divers ascended to a depth of 16.4 feet (5 m) where they remained for 19 minutes. As shown in Table 8-4, descending excursions to 229.6, 262.4, and 295.2 feet (70, 80, and 90 m) were made from the 65.6-foot (20 m) depth using a 50-50% air-helium breathing mixture. It was concluded from these experiments that a 90-10% nitrogen-oxygen breathing mixture was safe for long stays at a depth of 65.6 feet (20 m).

A 10-day saturation dive was made at a depth of 98.4 feet (30 m) with a breathing mixture of about 91-9% nitrogen-oxygen. Following a 3- to 5-day adaptation period, a total of 21 man-excursion dives were made.

A subsequent saturation dive was conducted at 131.2 feet (40 m) during which 42 man-excursions were made over 16 days. The breathing mixture at storage depth for both of the dives was nitrogen-oxygen in about a 94-6% mixture. The investigators reported that at the 131.2-foot (40 m) depth, psychological performance was impaired at the beginning but returned to normal after about 5 days. Apparently some of the descending excursions in these Soviet studies involved decompression prior to returning to the saturation depth, but the data were not reported.

The classic problem of extrapolating data obtained in the laboratory to a field situation has been addressed by Grinevich (1975*b*, p. 204):

> As our investigations showed, the chamber experiments are more difficult to tolerate than work in marine undersea laboratories. This is explained by the fact that, in the types PDK-3 and PDK-2 barochambers, the investigator is in either a sitting or prone position all the time. He cannot stand to his full height, he is not able to walk freely about the chamber and, even in the prone position, the investigator feels the inconvenience, because of the fact that the limited space does not permit him to extend to full height. During long exposures, this ultimately results in development of hypodynamia and reduction in work activity and, during decompression, it can favor the development of caisson disease. The readaptation phase after completion of decompression lasted from 3-4 to 8-10 days, and it ended with complete recovery of all physiological indices.

Grinevich concluded that saturation at a depth of 131 feet (39.9 m) with a nitrogen-oxygen breathing mixture of about 94-6% was not the maximum depth of saturation but that aquanauts chosen for deeper saturation on nitrogen-oxygen must be selected carefully and monitored closely.

EXPERIMENTS IN SPAIN

At about the same time the Chernomor studies were getting underway, a series of experiments on excursion diving was begun in Cartagena, Spain (A. DeLara, pers. commun. 1975 in Miller et al., 1976). This program was conducted under the auspices of the Spanish Navy and was referred to as the TONOFOND experiments. Ten saturation experiments, using three or four subjects each, were conducted between 1972 and 1975. Table 8-5 summarizes the results of these experiments and compares the excursion times with those of the NOAA-OPS study, which is described next.

EXCURSION DIVING PROFILES FROM NOAA

Perhaps the most significant study of vertical excursions was carried out from October 1972 to January 1973 at the Union Carbide Corporation, Tarrytown, New York. This program, referred to as NOAA-OPS, was supported by the NOAA. The purpose of the program was to develop and test decompression procedures and vertical excursion profiles, to study adaptation to nitrogen narcosis, and to assess further the stresses of 2 weeks of nitrogen saturation (Hamilton, et al., 1973). Tables were needed that would serve the entire depth range in which a nitrogen-based habitat might be located. Details of the computational basis for this study are contained in Hamilton et al. (1973) and Miller et al. (1976).

A technique was developed and used for extracting data from previous dives using a combination of computer and manual methods. This method produced successful tables on the first approach. The extensive studies conducted in the Soviet Union just described were not known at the time of the NOAA-OPS program and were not considered in the development of the model. Two 14-day, dry chamber saturation experiments were completed. Three subjects took part in each experiment, which involved saturation at depths of 30, 60, 90, and 120 feet (9.1, 18.3, 27.4, and 36.6 m). A total of 18 ascending and 15 descending excursions were completed successfully, constituting over 75 man-excursions. The breathing gas for the saturation exposures was a normoxic nitrogen-oxygen mixture. Air was breathed during all excursion dives.

The excursion depths were chosen to provide a good range of testing and to provide suitable exposures for performance monitoring. For example, exposures at 200 feet (61 m) and 250 feet (76.2 m) were repeated as often as possible to permit replication of tests during excursions.

Descending excursions included depths ranging from 80 to 300 feet (25.9-to-91.5 m), and ascents ranged from 30 to 65 feet (9.1 to 19.8 m)

Table 8-5. Summary of Spanish TONOFOND Experiments

Saturation Depth (ft)	Saturation Depth (m)	Experiment Number	Duration (Days)	Number of Divers	$\%O_2$	$\%N$	Excursion Depth (ft)	Excursion Depth (m)	Number of Air Excursions Bottom Time (min) 30	60	90	120	180	NOAA-OPS Excursion Limits
		1	3	3	14	86	130	39.6	1					140[a]
		2	3	3	14	86	130	39.6		2		3		140
		3	5	4	14	86	130	39.6		4		4		140
49	14.9	4	10	4	14	86	130	39.6		7		8		140
		5	3	4	12	88	130	39.6		1		2	1[b]	162[a]
		6	5	4	12	88	130	39.6		2		2	2[b]	162
							163	49.7		2[b]				44
65	19.8	7	10	4	12	88	130	39.6		4		4	4[b]	162
							163	49.7		2[b]	2[b]			44
		8	3	4	10	90	130	39.6					1	360[a]
							163	49.7				2		122[a]
							195	59.4		1[b]				32[a]
		9	5	4	10	90	163	49.7				2		122
81	24.7						195	59.4	2	2[b]				32
							227	69.2	2[b]					19
		10	10	4	10	90	163	49.7				4		122
							195	59.4	2	4[b]				32
							227	69.2	4[b]					19
							260	79.3	2					

[a] Actually tested in NOAA OPS.
[b] Times exceeding NOAA OPS.

Source: Derived from A. DeLara, Commandante Medico de la armada espanol, centro de buceo de la armada, La Algameca, Cartagena, Spain, in J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, 1976., *Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures,* National Oceanic and Atmospheric Administration, Rockville, Md., p. 12.

above the saturation depth. Excursion times ranged from 8 minutes to 6 hours. The ascending and descending excursions tested during the program are shown in Tables 8-6 and 8-7. When the descending excursion times derived for NOAA-OPS are compared with data in the Chernomor study (Table 8-4), it is seen that the former are consistently longer. Because of the lack of any significant signs or symptoms of decompression sickness, the computed allowable time for NOAA-OPS II was extended by 25% for the ascending excursions. These tests resulted in mild bends pain in one subject, suggesting that the original computations approached the safe limits.

The resulting saturation excursion diving tables have been published in the *NOAA Diving Manual* (Miller, 1979) together with detailed instructions as to their use. The tables appearing in the 1979 edition of the manual were modified to take into account high oxygen loadings encountered

Table 8-6. Excursions Computed and Tested, NOAA-OPS I

Day	Time	Depth (ft)	Depth (m)	Dive Time (min)	Remarks
1	1700	30	9.1		Go to 30 fsw
2		30	9.1		saturation depth
3	1000	120	36.6	62	
3	1400	120	36.6	60	
4	1000	85	25.9	316	
5	1000	200	61.0	10	
5	1400	200	61.0	10	
6	1000	100	30.5	104	
6	1400	100	30.5	100	
7	1000	150	48.8	30	
7	1400			30	
7	2000	90	27.4		Go to 90 fsw
8					saturation depth
9	1000	175	53.4	300	
10	1000	60	18.3	35	Ascending excursion
10	1400	40	12.2	20	Ascending excursion
11	1000	200	61.0	51	
11	1400	200	61.0	50	
12	1000	40	12.2	10	Ascending excursion
12	1400	60	18.3	35	Ascending excursion
13	1000	250	76.2	22	
13	1400	250	76.2	22	
13	1730	90	27.4		Begin decompression
14	1500				Decompression complete

Source: From R. Hamilton, D. Kenyon, M. Freitag, and H. Schreiner, 1973, *NOAA-OPS I and II. Formulation of Excursion Procedures for Shallow Undersea Habitats,* Technical Memorandum UCRI No. 731, July, Union Carbide Corp., Tarrytown N.Y., p. 42.

Table 8-7. Excursions Computed and Tested, NOAA-OPS II

Day	Time	Depth (ft)	Depth (m)	Dive Time (min)	Remarks
1	1900	0	0		Go to 120 fsw
2		120	36.6		saturation depth
3	1000	250	76.2	53	
3	1400	250	76.2	53	
4	1000	75	22.9	37	Ascending excursion
4	1400	55	16.8	9	Ascending excursion
5	1000	55	16.8	8	Ascending excursion
5	1400	75	22.9	39	Ascending excursion
6	1000	200	61.0	360	
7	1000	300	91.5	18	
7	1400	300	91.5	18	
7	1800	120	36.6		Begin decompression
8	0848	60	18.3		Arrive at 60 fsw
9	1000	150	45.7	72	saturation depth
9	1400	150	45.7	72	
10	1000	115	35.1	347	
11	1000	5	1.5	13	
11	1400	5	1.5	16	
12	1000	200	61.0	22	
12	1400	200	61.0	22	
12	1800	60	18.3		
13	1121	0	0		Begin decompression Surface

Source: From R. Hamilton, D. Kenyon, M. Freitag, and W. Schreiner, 1973, *NOAA-OPS I and II. Formulation of Excursion Procedures for Shallow Undersea Habitats,* Technical Memorandum UCRI No. 731, July, Union Carbide Corp., Tarrytown, N.Y., p. 43.

Note: In OPS II the computations were improved so as to account for compressions and decompressions. These were not included in bottom times. The tests followed the calculated profile quite closely.

in some of the longer excursions; thus, some excursion times are more conservative than the times shown in the experimental results.

The excursion tables resulting from the NOAA-OPS program were used extensively during the La Chalupa and Hydrolab programs. Hundreds of excursion dives have been made safely from these two habitats during the period 1972 to 1975 and again when the Hydrolab habitat became operational in 1978 at the present site in St. Croix, U.S. Virgin Islands.

THE NAVY'S SHALLOW HABITAT AIR DIVING PROGRAM (SHAD)

Following the completion of the NOAA-OPS program, the U.S. Navy conducted a series of laboratory studies on air saturation during 1973-1974 referred to as SHAD. Conducted at the Naval Submarine Medical Research

Laboratory (NSMRL), SHAD was designed to evaluate further the biomedical feasibility of long-term residence in a compressed air environment and to establish vertical excursion profiles that could be used by air-saturated working divers (Adams et al., 1978). Emphasis was on pulmonary physiology, visual physiology, psychophysiology, hematology, and the chemistry and biochemistry of both urine and blood (Miller et al., 1976; Hamilton et al., 1982). The fundamental difference between this program and NOAA-OPS was that the SHAD divers breathed air both as a storage and excursion gas.

The initial studies involved a 60-day exposure of rats at a depth of 50 feet (15.2 m) and a 36-day exposure at 60 feet (18.3 m) (Murray et al., 1974). This was followed by a 3-day manned air exposure, referred to as pre-SHAD, at a depth of 50 feet (15.2 m). The experimental design required that humans be placed at 50 and 60 feet (15.2 and 18.3 m) for a maximum of 30 days. A no-decompression excursion dive regimen permitting excursions between 5 and 240 feet (1.5 and 76.2 m) was constructed on a mathematical basis similar to that employed in the NOAA-OPS I and II program. All subjects taking part in SHAD had volunteered and were qualified U.S. Navy divers under 30 years of age.

Four manned air saturation dives were carried out totaling 3516 man-hours of air saturation. The general characteristics of these dives are shown in Table 8-8. Significant environmentally related medical changes were not observed during the saturation periods although a minor external otitis was observed during SHAD I and II, which responded to routine treatment. The health problems, both medical and dental, that did occur were typical of those normally encountered at the surface.

Eight ascending and 31 descending excursions were conducted between the depths of 5 and 250 feet (1.5 and 76.2 m) without encountering any serious problems (Table 8-9). The excursions undertaken during SHAD III, while only to a depth of 100 feet (30.5 m), lasted for periods up to 478 minutes to simulate an 8-hour working day on the seafloor. Near-baseline levels were reached during the intervening residence periods at the 50-foot (15.2 m) saturation level.

Three of the nine divers participating in the SHAD experiments had symptoms of decompression sickness. In each case, a combination of recompression and pure oxygen breathing was employed in the therapeutic treatment, and on each occasion changes indicative of oxygen toxicity were observed (Adams et al., 1978). Although there were no symptoms of oxygen toxicity at storage depth, the consistent observation of such symptoms and/or related changes during bends treatment cannot be overlooked and must be taken into account when planning air saturation missions. These changes suggest that some alteration occurred in the divers that precluded their ability to accommodate to what normally would be a routine treatment procedure employing 100% oxygen.

Table 8-8. General Characteristics of SHAD DIVES

Dive / *Date*	*Pre-SHAD, I* *Sept 1973*	*SHAD, I* *Oct 1973*	*SHAD, II* *Mar 1974*	*SHAD, III* *Dec 1974*
Storage depth (ft/m)	50/15.2	50/15.2	60/18.3	50/15.2
Number of divers	2	2	2	3
Duration, total (days)	2.25	29.5	28	9
Mean oxygen level (ATA)[a]	0.51	0.51	0.57	0.61
Mean carbon dioxide level[a,b]	0.111	0.092	0.099	0.172
Mean temperature (°F)[a]	78.0	76.8	73.0	75.8
Mean relative humidity (%)[a]	76.0	62	52	74.7
Number ascending excursions	0	4	4	0
Number descending excursions	0	14	11	6
Decompression time (min)	57.4	810	1680	2778[c]
Decompression sickness[d]	Yes (2)	No	No	Yes(1)

Source: From J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, 1976, *Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures,* National Oceanic and Atmospheric Administration, Rockville, Md., p. 37.

Note: Compressed air with oxygen makeup was the only gas employed.

[a] Storage depth values except for SHAD III, where a weighted mean reflective of the 8 hours per excursion day spent at 100 feet was employed.

[b] Percent, surface equivalent.

[c] Includes treatment regimen with 100% oxygen and recompression.

[d] Parentheses indicate number of divers affected.

Table 8-9. Summary of Excursion Times for the SHAD Program (Time in Minutes)

Saturation Depth			*Excursion Depth*						
(ft)	*(m)*	*Ft* / *m*	*5* / *1.5*	*15* / *4.6*	*100* / *30.5*	*150* / *45.7*	*200* / *61*	*235* / *71.6*	*250* / *76.2*
SHAD I									
50	15.2		31	54-57	58	43	18	6	
SHAD II									
60	18.3		21	31	60	60	20		6
SHAD III									
50	15.2				478				

Source: After J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, 1976, *Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures,* National Oceanic and Atmospheric Administration, Rockville, Md.

Note: Total number of excursions equals 39.

Ascending excursions involving a maximum pressure differential of 1.67 atm. (55 feet, 16.8 m) were evaluated. They were used in both nonrepetitive and repetitive combinations with descending excursions. No symptoms of decompression sickness occurred except for skin itching, which is commonly found in dry chamber divers. Circulating gas bubbles

occasionally were detected by a bubble detector at the end of the excursion periods. Bubbles were not detected after the repetitive descending excursions that followed the ascending excursions. The SHAD program further documented the feasibility of human residence in air at 50 and 60 feet (15.2 and 18.3 m) for extended periods, as well as the availability of an air excursion matrix ranging from 5 to 250 feet (1.5 to 76.2 m). Significant insight into the ranges of oxygen partial pressures to which humans can accommodate also was acquired. The higher oxygen partial pressures experienced while at storage depth, however, seem to be a potential hazard if oxygen treatment is necessary. Further work needs to be done to better understand and reduce this hazard.

SCORE, A JOINT GOVERNMENT-UNIVERSITY-INDUSTRY PROGRAM

The SCORE (Scientific Cooperative Operational Research Expedition) program involved the cooperative efforts of the NOAA, the Harbor Branch Foundation of Fort Pierce, Florida, and the F. G. Hall Laboratory of the Duke University Medical Center. The purpose of the program was to extend useful bottom time at a saturation depth of 60 feet (18.3 m) through the use of excursion profiles that included decompression prior to returning to the saturation depth. Tests also were included to determine whether there was any impairment of cognitive, psychomotor, or physiological functions during the saturation or excursions.

The first phase of the program took place at Duke University from January 27 to February 10, 1975. Two teams of four men each were selected, all experienced divers ranging in age from 26-40. Complete medical examinations were given both before and after the saturation exposure. Performance and cognitive tests were administered to measure the effects of nitrogen narcosis.

Control studies were conducted at the excursion depths of 200, 250, and 300 feet (61, 76.2, and 91.5 m) during which the subjects descended from the surface and remained for 15 minutes to take performance tests. Further control data were obtained on reaching the 60-foot (18.3 m) saturation depth. During all excursions, performance tests were administered and blood samples obtained. A 300-foot (91.5 m) dive also was conducted the day following the final decompression as a postdive control. Experiments to test for possible adaptation to increased nitrogen partial pressures were run before and after the dive, as well as at the saturation depth and during excursions.

The following criteria were used in the computation of all excursion profiles:

Breathing gas: air (20% oxygen, balance nitrogen).
Saturation level: 65 feet (19.8 m), divers returning to 60 feet (18.3 m).
Instantaneous compression to excursion depth.
Excursion calculated at a depth 5 feet (1.5 m) greater than that listed for the profile.
Initial ascent rate: 30 feet (9.1 m) per minute.
Rate of ascent between stops: 10 feet (3 m) per minute.
Decompression stop time: rounded to next whole minute.

The excursion diving profiles for the laboratory study are shown in Table 8-10. No indications of bends were detected during either the 200-foot (61 m) or 250-foot (76.2 m) excursions, although at 250 feet there were symptoms indicative of oxygen toxicity. The results of the 300-foot excursions were more severe; one subject experienced oxygen convulsions.

The performance tests for signs of nitrogen narcosis and/or adaptation to it showed a slight improvement in performance at 60 feet (18.3 m) during the saturation. A considerable decrement in performance was found during the 300-foot (91.5 m) excursions compared to data obtained at 200 and 250 feet (61 and 76.2 m). There appeared to be some improvement in performance during the 200- and 250-foot excursions compared to that shown in the initial dives to those depths from the surface, although

Table 8-10. Excursion Decompression Profiles for a 60-Foot Habitat Tested During SCORE Laboratory Studies (Time in Minutes)

Excursion Depth		*Excursion Time*	*Stop time (min)/Stop depth (ft)*									*Total Ascent*
(ft)	*(m)*	*(min)*	*150*	*140*	*130*	*120*	*110*	*100*	*90*	*80*	*70*	*time*[a]
		30									3 1/3	9
200	61	60							5 1/3	4	3	19
		30							6 2/3	4	3	22
250	76.2	60				2/3	3	7	6	9	9	45
		15							1	4	3	18
		30					1 2/3	7	6	4	4	34
300	91.5	45			2 1/3	3	3	7	7	9	10	55
		60	2	3	3	3	5	10	10	9	44	103

Source: From J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, 1976, *Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures,* National Oceanic and Atmospheric Administration, Rockville, Md., p. 52.

[a] Ascent time to first stop was 30 ft/min. Ascent time between stops was 10 ft/min

this could have been due to learning. It was concluded that there was insufficient evidence to support the theory that there was adaptation to nitrogen narcosis (Miller, 1978). Based on the risk of oxygen convulsions, it was recommended that no compressed air excursions be made to 300 feet (91.5 m) when saturated at a storage depth of 60 feet (18.3 m) with air as the breathing mixture (Miller et al., 1976). Due to symptoms of bends during decompression from the 300-foot (91.5 m) excursion, it was recommended further that excursion times to 250 feet (76.2 m) be reduced from 60 minutes to 45 minutes under open sea-conditions.

The open-sea phase of SCORE was carried out from April 1 to 27, 1975, two months after the completion of phase I. The facilities included the Hydrolab habitat, the Johnson Sea Link diver lockout submersible, and several seafloor shelters similar to those shown in Figure 6-11. The overall layout of the SCORE project is shown in Figure 4-18.

Sixteen aquanauts in teams of four were saturated in Hydrolab at a depth of 60 feet (18.3 m) on air for 5 days each. Excursions were made to a depth of 200 feet on air by swimming from the habitat over the edge of the wall to the designated location (Fig. 4-18). At the end of the excursion, the aquanauts swam back to Hydrolab, stopping at the depths prescribed in the decompression profiles shown in Table 8-11.

Table 8-11. Decompression Schedules for Excursions to 200 and 250 Feet from Saturation at 60 Feet for SCORE Open-Sea Tests

200 ft (61 m) Excursion					*250 ft (76.2 m) Excursion*		
Depth		*Ascent Rate*		*Time*	*Ascent Rate*		*Time*
(ft)	*(m)*	*(ft)*	*(m)*	*(min)*	*(ft)*	*(m)*	*(min)*
250-120	76.2-36.6				30	9.1	4 1/3
200-90	61.0-27.4	30	9.1	3 2/3			
120-stop	36.6						2/3
120-110	36.6-33.5				10	3.0	1
110-stop	33.5						3
110-100	33.5-30.5				10	3.0	1
100-stop	30.5						7
100-90	30.5-27.4				10	3.0	1
90-stop	27.4			5 1/3			6
90-80	27.4-24.4	10	3.0	1	10	3.0	1
80-stop	24.4			4			9
80-70	24.4-21.3	10	3.0	1	10	3.0	1
70-stop	21.3			3			9
70-60	21.3-18.3	10	3.0	1	10	3.0	1
TOTAL				19			45

Source: From J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, 1976, *Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures*, National Oceanic and Atmospheric Administration, Rockville, Md., p. 97.

For the 250-foot (76.2 m) excursions, the aquanauts entered the diver lockout compartment of the Johnson Sea Link submersible at the Hydrolab and were transported to the excursion depth. When they reached the 250-feet depth, the pressure in the submersible dive compartment was equalized with the ambient pressure, and the hatch opened, allowing the aquanauts to exit. After completion of the excursion, the aquanauts reentered the dive compartment, closed the hatch, and were transported back to Hydrolab, where they remained inside the submersible to complete the decompression as shown in Table 8-11.

Thirty-four man-excursions were made to 200 feet (61 m) and thirteen to 250 feet (76.2 m). Because of the results of the SCORE laboratory study, no excursions were made to 300 feet (91.5 m). One swimming and one submersible lockout excursion was scheduled each day. A given aquanaut, however, made either a submersible or a swimming excursion—never both in a single day. The basic descent and ascent excursion profiles were the same for all excursions, although the bottom profiles during the excursions varied depending on the nature of the marine science mission. No symptoms of bends were experienced during decompression back to the 60-foot (18.3 m) storage depth. The project was marred only by a near-fatal accident that occurred during the first swimming excursion. (The incident is described in Chapter 7.)

Project SCORE demonstrated clearly the feasibility of conducting working decompression excursion dives on air to depths of 250 feet (76.2 m) from an air saturation storage depth of 60 feet (18.3). If inert gas narcosis was present, it was not of sufficient magnitude, in the opinion of aquanauts or observers, to impair cognitive or psychomotor performance (Miller, 1978).

EXCURSION DIVING FROM HYDROLAB

Prior to the availability of the NOAA-OPS vertical excursion profiles in 1973, excursions from Hydrolab beyond a depth of 90 feet (27.4 m) were not permitted. This was a safe practice since even the most conservative NOAA OPS excursion profiles allow unlimited excursion time at 90 feet (27.4 m) from either a 40- or 60-foot saturation depth.

During 1973-1975 100 no-decompression and 4 decompression excursion dives were made from a 42-foot (12.8 m) saturation depth to depths greater than 125 feet (38.1 m) and 200 feet (61 m), respectively. In October 1973, 16 no-decompression excursions were made by two aquanauts to depths ranging from 50 to 200 feet (15.2 to 61 m). No symptoms of bends were noted during any of these excursions, which are summarized in Figure 8-1. Figure 8-2 illustrates the excursion profile used by 25 aqua-

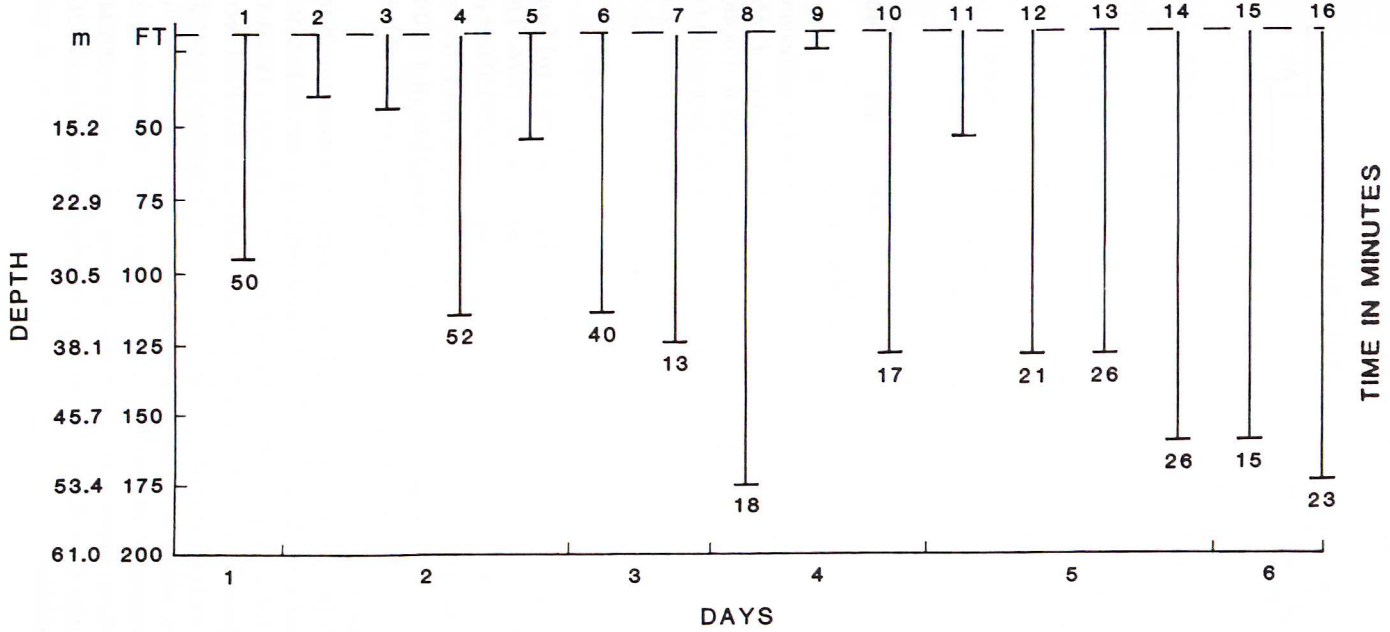


Figure 8-1. Summary of 16 no-decompression excursions made by two hydrolab aquanauts from air saturation at 42 feet (12.8 m). *(After J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures, National Oceanic and Atmospheric Administration, Rockville, Md., p. 70.)*

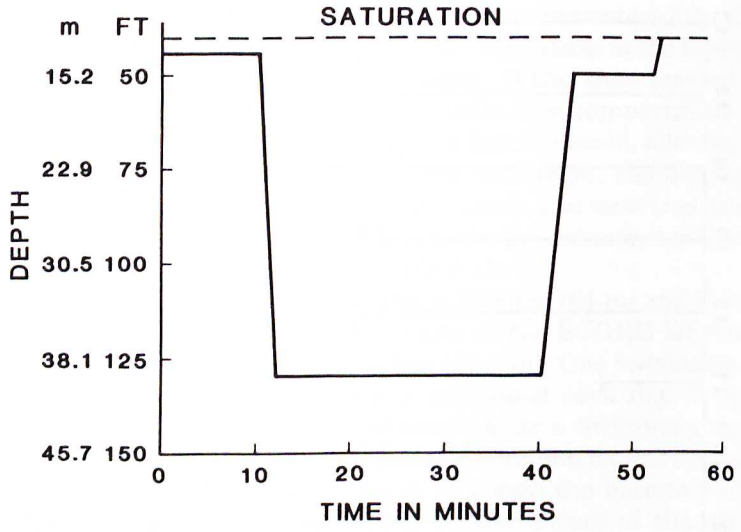
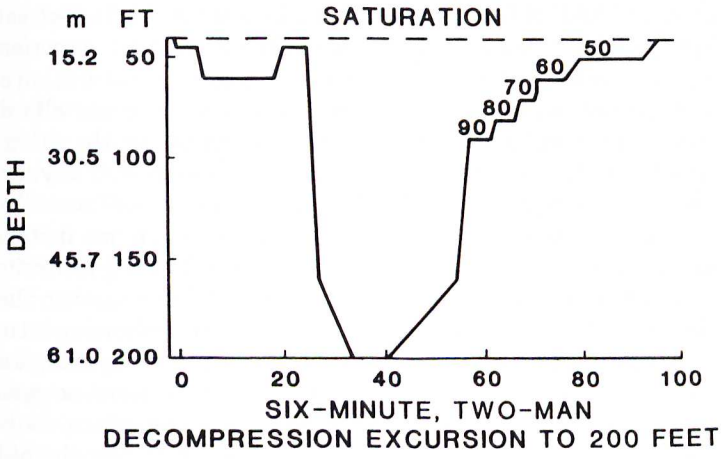


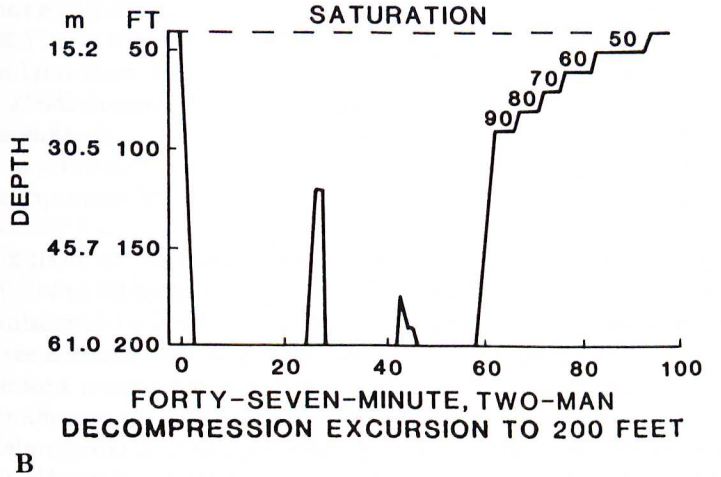
Figure 8-2. No-decompression profile used by 25 aquanauts for excursions to 130 feet (39.6 m) from air saturation at 42 feet (12.8 m). *(After J. Miller, G. Adams, P. Bennett, R. Clarke, R. Hamilton, D. Kenyon, and R. Wicklund, Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures, National Oceanic and Atmospheric Administration, Rockville, Md., p. 71.)*

nauts when making excursions to a depth of 130 feet (39.6 m) from a saturation depth of 42 feet (12.8 m) in July and August 1974. These excursions required each aquanaut to swim approximately 3000 feet (915 m) and involved a 33-minute bottom time. No symptoms of bends occurred during any of these excursions. The maximum bottom time of a 130-foot (39.6 m) no-decompression excursion is 70 minutes, so the lack of bends was not surprising.

During 1973-1974, many additional excursion dives were made from the 42-foot (12.8 m) Hydrolab depth to depths ranging from 80 to 200 feet (24.4 to 61 m). Detailed profiles are contained in Miller et al. (1976). One series of excursions is particularly noteworthy because it involved decompression stops on the return to the 42-foot (12.8 m) Hydrolab saturation depth. These excursions are shown in Figure 8-3. The excursions cited, plus those described in Miller et al. (1976), were made without mishap and increased the confidence of those involved regarding the potential of extending the useful working time and depths for aquanauts operating from seafloor habitats.



A



B

Figure 8-3. Decompression excursion dives made from Hydrolab habitat. *A*: Six-minute two-man decompression excursion to 200 feet. *B*: Forty-seven minute two-man decompression excursion to 200 feet.

FIELD STUDIES IN GREAT BRITAIN AND NEWFOUNDLAND

In 1966, the British launched a habitat named Bubble in the Maltese Islands in which the saturation exposure was on air at a depth of 31 feet (9.4 m). One of the interesting features from the standpoint of saturation diving is that a major objective of the project was to determine if the

aquanauts could ascend directly to the surface from the 31-foot saturation depth within 2 minutes and remain there without experiencing decompression sickness. Seven 12-hour and two 24-hour saturation exposures were carried out during which the aquanauts were not allowed to make excursions either above or below the saturation depth.

The results of these experiments revealed no evidence of any form of decompression sickness after spending 12 hours on the seafloor. The two 24-hour exposures, however, produced complications. In one instance, a classical joint bend in the knee occurred 12 hours following return to the surface, which required recompression in the shore chamber. In the second instance, the aquanaut was awakened 36 hours following return to the surface with pain in both eyes and was unable to see anything except light and dark. These symptoms abated, and there were no residual effects. In the first case, the 24-hour exposure took place 45 hours following a previous 12-hour exposure. In the second instance, the 24-hour exposure was 67½ hours after a 12-hour exposure.

In 1973 two aquanauts spent 24 hours in the LORA habitat in the icy waters of Newfoundland breathing air at a depth of 26 feet (7.9 m). During the saturation exposure, excursions were made on several occasions to a depth of 35 feet (10.7 m). After spending 8 hours at the 26-foot saturation depth following the last excursion to 35 feet, both aquanauts ascended directly to the surface without any decompression stops. Neither aquanaut experienced any signs or symptoms of decompression sickness.

A similar 29-hour saturation mission was conducted in LORA two years later in February 1975, also at a saturation depth of 26 feet (7.9 m). Excursions were made to depths of 35 feet (10.7 m). Instead of waiting for 8 hours after the last excursion, this time the aquanauts breathed oxygen for six 20-minute periods with 5-minute periods in between breathing habitat air. The purpose of this procedure was to allow the aquanauts to surface as quickly as possible following the last excursion. On completion of the oxygen breathing, they ascended directly to the surface. No signs or symptoms of decompression sickness were noted.

Although the data obtained during the Bubble and LORA habitat programs are based on only a few exposures, they suggested that a safe no-decompression ascent may be possible from 26 feet (7.9 m) but not from 31 feet (9.4 m) following saturation on air. It was clear that additional work was needed to pinpoint the maximum air saturation depth from which a no-decompression ascent can be made. Additional data will be useful in the future when planning shallow-water scientific, educational, or recreational projects where the goals are to use the maximum safe depths for observational purposes without the need for decompression.

NITROGEN SATURATION STUDIES IN THE NAVY (NISAT)

About the same time that the open-sea phase of the SCORE project was getting underway, the navy resumed its nitrogen-oxygen studies at the Naval Submarine Medical Research Laboratory, New London, Connecticut. The NISAT series included three separate saturation exposures with three subjects participating in each dive.

In NISAT-I, which took place in March 1975, three subjects lived and worked at a depth of 198 feet (60.4 m) for 7 days while breathing a normoxic mixture of 97.03% nitrogen and 2.97% oxygen. According to Hamilton et al. (1982, p. I-9), the purpose of the dive "was to verify that decompression could be carried out from the deepest depth that might reasonably be needed for treatment following a nitrox-heliox switch. A secondary objective was to study the effects of several days exposure to high nitrogen pressures." Various medical and psychological tests were administered during the exposure. Two of the divers experienced nausea for the first day, and all three experienced a variety of symptoms during the entire exposure, including joint pains, drowsiness, numbness, difficulty with breathing, and continual cold clammy feeling. As might be expected in such a high nitrogen atmosphere, there was clear evidence of nitrogen narcosis throughout the dive, although the symptoms varied in type and severity.

NISAT-I was a highly stressful experience and resulted in fatigue both during the exposure and following the 161-hour decompression. The degree of stress is indicated by the fact that task performance at depth was reduced, the divers felt distressed throughout the dive, and several incidents such as vomiting, slurred speech, decrement of pulmonary functions, and changes in heart rhythms and brain waves were observed (Hamilton et al., 1982). In the opinion of the investigators, these problems suggest that the divers were approaching their functional limits with respect to health and their capability to perform work.

NISAT-II, which took place in June 1976, was a 3-day saturation exposure using a normoxic nitrogen-oxygen breathing mixture at a depth of 66 feet (20.1 m). This experiment was to determine the effects of switching abruptly from nitrogen to helium while maintaining the same partial pressure of oxygen. The reason for conducting this study was the possible use of the technique in submarine rescue (Hamilton et al., 1982).

Generally NISAT-II was much less stressful than NISAT-I. Although the divers did not suffer the adverse effects experienced in NISAT-I, there was an extended period of severe skin itching for about the first 9 hours following the switch from nitrogen to helium, which was symptomatic of

skin bends. On the positive side, the divers all felt less sleepy and breathing was easier after the switch to helium. Following the dive, the subjects were decompressed for 28.7 hours to the surface.

NISAT-III, which took place in June and July 1976, also was a 3-day saturation exposure and followed the same basic profile as used in NISAT-II except that the saturation depth was 99 feet (30.2 m). The main objective was to determine the physiological effects of an abrupt switch from normoxic nitrogen-oxygen to a comparable helium-oxygen breathing media. Very severe itching was experienced by all subjects when switching to helium. In addition, all divers experienced pain or discomfort in the thighs and knees for several hours after the switch, problems that dissipated subsequently in two of the subjects. The third had severe pain, and as a result the pressure in the chamber was increased to a depth of 129 feet (39.3 m), at which point the pain subsided. The 54-hour decompression to the surface from 129 feet (39.3 m) was uneventful (Hamilton et al., 1982).

The NISAT series of saturation divers demonstrated that 198 feet (60.4 m) is too deep to use a nitrogen-oxygen breathing mixture and that such a mixture is not a practical means of conducting work on the seafloor. On the other hand, "switching from nitrogen to helium, greatly improves the chances of a safe and relatively fast saturation decompression" (Hamilton et al., 1982, p. VIII-5). Figure 8-4 shows the general saturation and decompression profiles for the NISAT series.

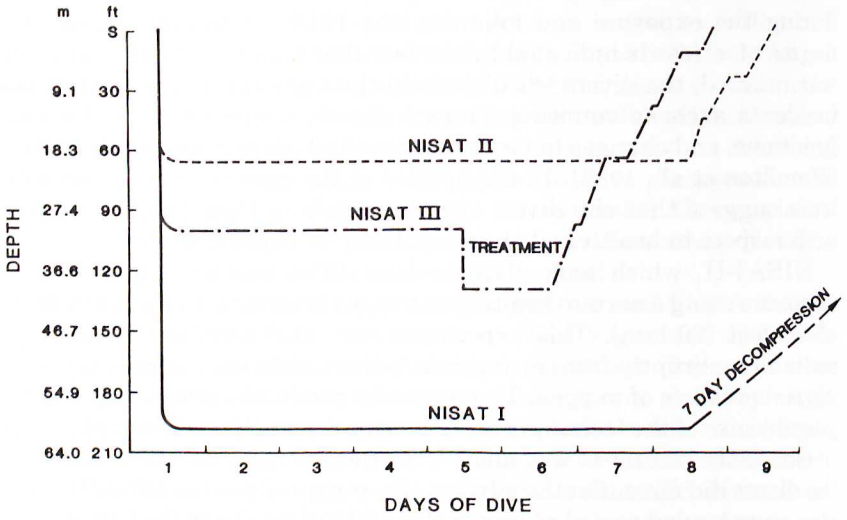


Figure 8-4. Summary of U.S. Navy nitrogen saturation (NISAT) dive profiles. (Courtesy of U.S. Navy)

AIR SATURATION STUDIES IN THE NAVY (AIRSAT)

In March 1977 another series of saturation dives was undertaken by the navy, again in the New London Laboratory. The basic difference between these experiments and the NISAT series was that air was used as the breathing medium, and descending excursions were made from the storage depth.

AIRSAT-I was divided into phases A, B, and C, which took place in March, May, and July, respectively, 1977. Four subjects were used in phases A and B and three subjects in phase C. The saturation, excursion, and decompression profiles were the same in all three phases. The subjects were saturated on air at a depth of 60 feet (18.3 m) for 7 days. Five 8-hour descending excursions were made to a depth of 100 feet (30.5 m) during the 7-day saturation. One excursion was made each day for days 2 through 6. On the seventh day the subjects rested and began their 20-hour decompression to the surface. The AIRSAT-I protocol is shown in Figure 8-5.

AIRSAT-II consisted of four saturation exposures with three subjects in each dive. These experiments were carried out in September and November 1977, March 1978, and February 1979. The storage depth again was 60 feet (18.3 m), where the subjects remained for 8 days. Six descending excursions were made during this period, one each on days 2 through 7. On all excursions, the subjects were pressurized to a depth of 150 feet (45.7 m) for 2 hours. Air was breathed on the excursions, as well as at the storage depth. A 2 hour and 40 minute decompression was required for the return to the 60-foot (18.3 m) storage depth, as shown in Table 8-12. As in AIRSAT-I, the final decompression time to the surface was 20 hours. The total dive profile is shown in Fig. 8-6.

Table 8-12. Decompression Schedule for Return to 60-Foot Storage Depth Following Two-Hour Descending Excursions to 150 Feet During AIRSAT-II

Depth		*Time*	
(ft.)	*(m)*		*(min)*
150	45.7	Lv	00:00:00
90	27.4	Arr	00:02:00
90	27.4	Lv	00:22:00
80	24.4	Lv	01:02:00
70	21.3	Lv	02:42:00
60	18.3	Arr	02:42:20

Notes: All travel at 30 feet (9.1 m) per minute. Total decompression time: 2 hrs, 42 min, 20 sec.

Source: Data courtesy of U.S. Navy.



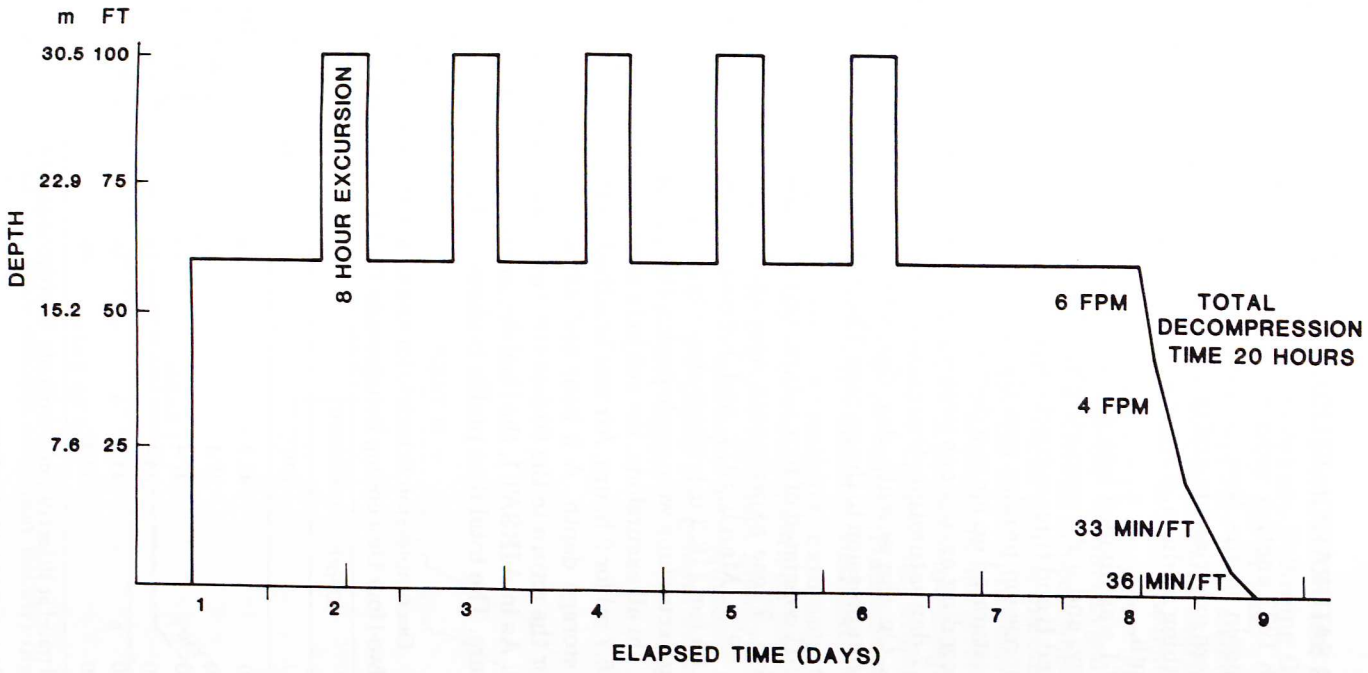


Figure 8-5. Dive protocol for AIRSAT I. (Data courtesy of U.S. Navy)

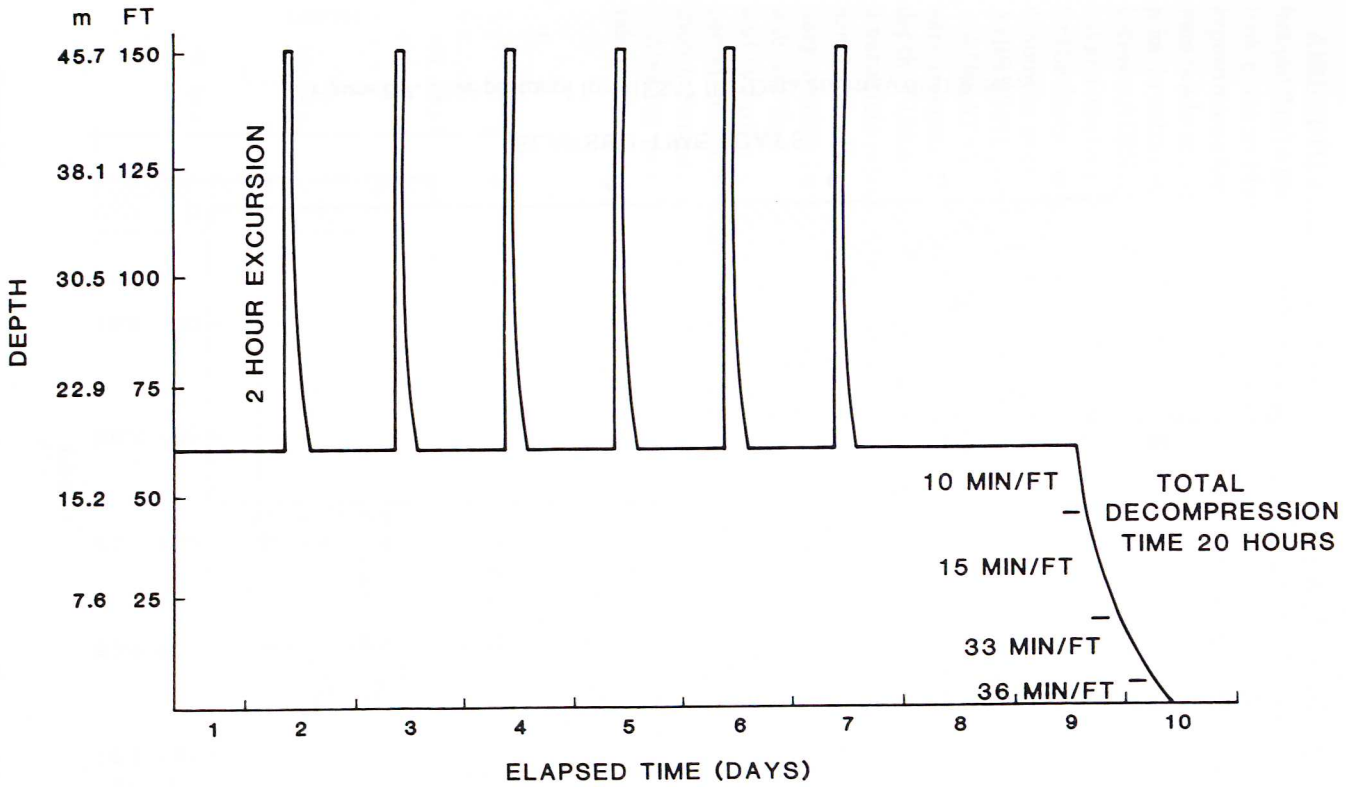


Figure 8-6. Dive protocol for AIRSAT II. (Data courtesy of U.S. Navy)

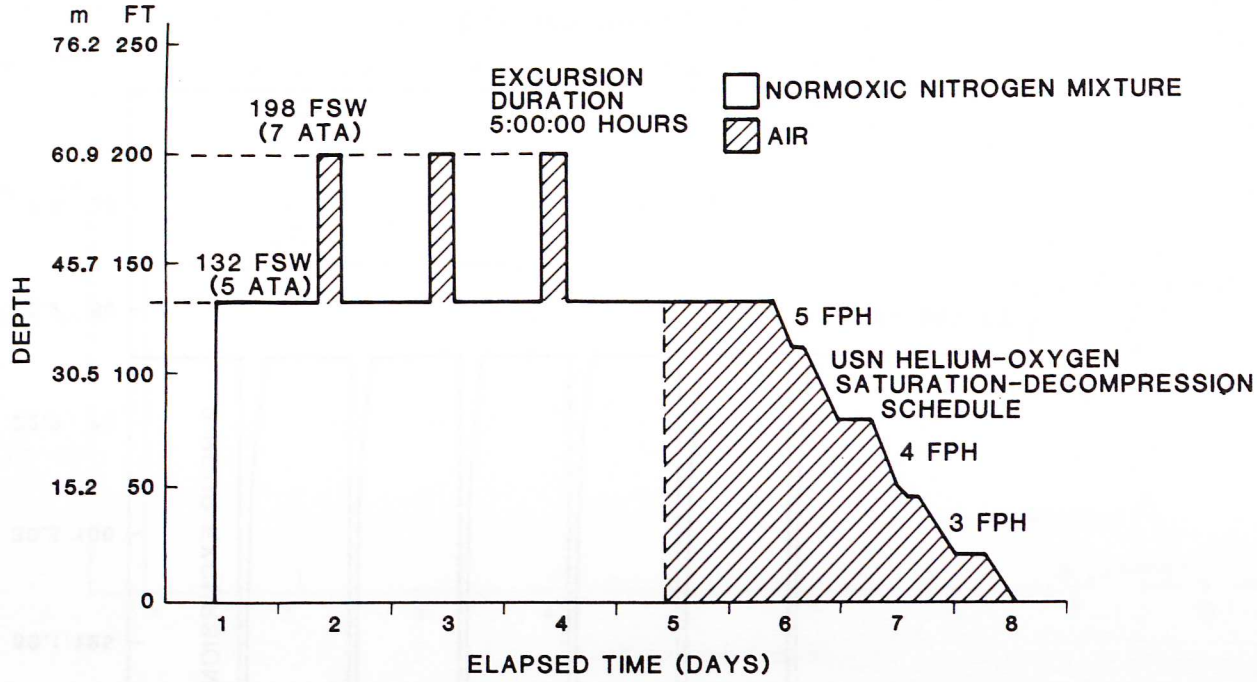


Figure 8-7. Dive protocol for AIRSAT III. (Data courtesy of U.S. Navy)

AIRSAT-III consisted of three saturation exposures to a depth of 132 feet (40.2 m) with three subjects participating in each dive. These studies took place in May 1979 and February and April 1980. Each saturation exposure was for 5 days during which three 5-hour descending excursions were made to a depth of 198 feet (60.4 m). There was no decompression prior to returning to the 132-foot (40.2 m) storage depth. A difference between AIRSAT-III and AIRSAT-I and II was that a normoxic nitrogen-oxygen mixture was breathed at the storage depth, and air was used only for the descending excursions. Air also was used for the final 50-hour and 44-minute decompression to the surface on completion of the dive. The AIRSAT-III profile is shown in Figure 8-7.

AIRSAT-IV, conducted in 1982-1983, was designed to study pulmonary oxygen toxicity in humans exposed to 5 ATA air, equivalent to a depth of 132 feet (40.2 m), for 48 hours. The subjects were first exposed to a normoxic nitrogen mixture for 12 hours followed by the 48-hour exposure to air. The AIRSAT-IV dive profile is shown in Figure 8-8. Preliminary results based on 9 of the 15 subjects taking part in the study indicate that "besides the fact that all subjects suffer significant signs and symptoms of pulmonary oxygen toxicity by the end of the 48 hour period, recovery in a 0.5 ATA atmosphere occurs" (Eckenhoff, pers. commun.). Further experiments in the AIRSAT series are planned for 1984.

Another program carried out by the navy's New London laboratory, referred to as SUREX (Surface Excursion), was designed to examine the

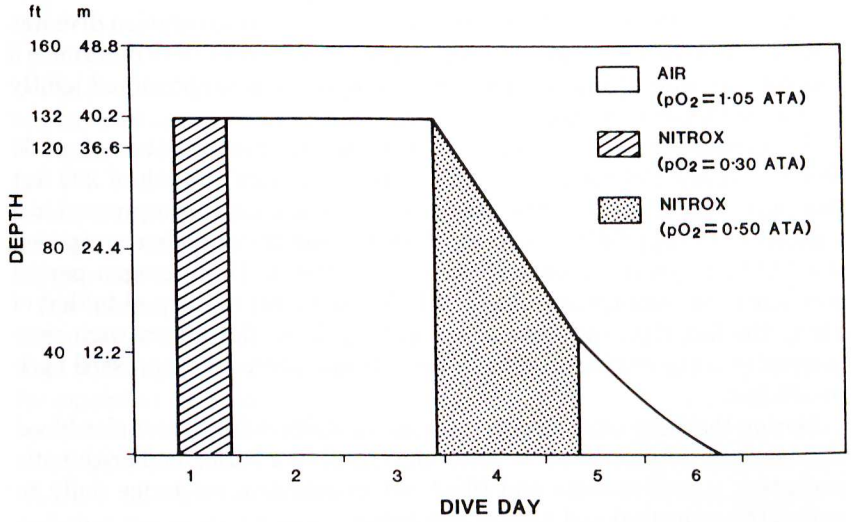


Figure 8-8. Dive protocol for AIRSAT IV. (Data courtesy of U.S. Navy)

safe surface interval following saturation on nitrogen-oxygen breathing mixtures. Such studies are important for establishing operational procedures for future habitat programs in the event that an aquanaut surfaces accidentally. In this study, eighteen human subjects were saturated on air at depths of 45, 55, and 65 feet (13.7, 16.8, and 19.8 m). Excursions to the surface were made for 30, 17, and 10 minutes, respectively. No serious decompression sickness was reported during any of the excursions. The results of the surface excursions from 45 and 55 feet (13.7 and 16.8 m) "probably indicate that the durations are maximal for routine operational use, yet probably leave some flexibility for the true emergency application" (Eckenhoff and Parker, 1982, p. 6). Based on the 7- and 10-minute excursions from 65 feet (19.8 m), these same investigators "believe that an excursion of at least 12 minutes from air saturation at 65 fswg will be tolerated with an acceptable level of decompression sickness (defined here as 1-10% incidence)." [p. 6]

The Navy's program in New London has provided valuable new data on air and nitrogen saturation excursion diving. Extensive biomedical and psychological studies were carried out as part of the AIRSAT and SUREX program. The details of these studies and the results were not available at the time of publication.

DUKE UNIVERSITY-NOAA-OCEANEERING NITROGEN-OXYGEN SATURATION DIVE

From April 19 to 27, 1982, a deep nitrogen-oxygen saturation dive was conducted at the F. G. Hall Laboratory of Duke University to determine if humans can adapt to nitrogen narcosis. The study was sponsored jointly by the NOAA and Oceaneering International, Inc.

Ten experienced divers (ages 22 to 42) were compressed at a rate of 60 feet per minute (18.3 m per min) in air to a simulated depth of 200 feet (60.1 m). After 2 hours at this depth, the divers were decompressed in 2 minutes to 165 feet (50.3 m) and transferred to another chamber containing 0.5 ATM oxygen in nitrogen (Barry et al., 1983). The nitrogen partial pressure in the storage chamber at 165 feet (50.3 m) was equal to that of air at 200 feet (60.1 m). Over a period of 4 days, the divers were compressed in air to 200 feet for 2-hour periods and then decompressed back to 165 feet.

During the 9-day experiment, medical tests, including extensive blood studies, were administered. In addition, the divers performed arithmetic and other cognitive tests and filled out questionnaires twice daily to assess their physical and mental well-being.

While there were differences among the divers, all showed definite

signs of nitrogen narcosis during the exposure. According to Dr. David Youngblood, the investigator for Oceaneering International:

> There were two phases of improvement. The first one occurred after a few hours, and this we believe to be an adjustment to the state of narcosis and not a true reduction in it. The second period of performance improvement occurred after several days. A large percentage of the divers showed a significant improvement in their test scores, and this is believed to be a true physiological adaptation to high nitrogen pressure (Stringer, 1983, p. 128).

The youngest diver in the group who experienced his first saturation dive said, "During the first five days, everything amused me. When we began our ascent, I realized that I had been narced out" (Stringer, 1983, p. 129).

Decompression from the 165-foot (50.3 m) saturation depth was uneventful until the 65-foot (19.8 m) level was reached, at which time several divers experienced symptoms of decompression sickness and required treatment by recompression and/or additional oxygen breathing. As a result, the proposed decompression schedule of 71 hours was extended. One diver even developed decompression sickness 68 hours after leaving the chamber during a flight in a pressurized aircraft and required treatment after landing. It was clear to the investigators that additional studies are needed to develop suitable decompression schedules for deep nitrogen-oxygen saturation exposures (Barry et al., 1983).

SUMMARY

The results of the studies reviewed in this chapter have shown that air or mixtures of nitrogen and oxygen can be used alone or in combination for undersea habitats and for making excursion dives to depths up to 250 feet (76.2 m). For depths in excess of 250 feet, the available evidence favors the use of helium-oxygen mixtures. In fact, most commercial diving operations at depths beyond 150 feet (45.7 m) have used helium-oxygen mixtures for years.

Air has been the breathing gas of choice for most habitat programs because it is the least expensive, many programs took place at depths less than 50 feet (15.2 m), and within this depth range, air can be used safely for extended exposures. Beyond 50 feet, it is felt that the use of air for saturation exposures increases the probability of oxygen toxicity. It is recommended, therefore, that for depths between 50 and 115 feet (15.2 to 35.1 m), mixtures of nitrogen-oxygen be used for saturation exposures and that the partial pressure of oxygen be maintained within a range of 0.2 to 0.5 ATA Miller (1979). It should be made clear, however, that while

the limiting factor for the use of oxygen is pulmonary oxygen toxicity, the limiting factor for nitrogen is the well-known inert gas narcosis, which affects judgment, memory, and the ability to perform mental or motor skills.

Table 8-13 presents examples of ascending and descending excursion times for four representative saturation depths based on the NOAA-OPS I and II studies (Hamilton et al., 1973). The complete tables of excursions based on these studies are contained in the NOAA Diving Manual (Miller, 1979).

Table 8-13. Ascending and Descending Excursion Times (min) from Four Representative Saturation Depths

	Depth (ft)	Depth (m)				
Ascending excursions	0	0	36	0	0	0
	10	3.0	60	13	0	0
	20	6.1	[a]	25	0	0
	30	9.1		42	5	0
	40	12.1		[a]	16	0
	50	15.2		[a]	30	0
	60	18.3			48	7
	70	21.3			[a]	18
	80	24.4			[a]	32
	90	27.4				60
	100	30.5				[a]
Saturation Depth (ft/m)			30/9.1	60/18.3	90/27.4	120/36.6
Descending excursions	40	12.1	[a]			
	60	18.3	[a]			
	80	24.4	350	[a]		
	100	30.5	91	[a]	[a,b]	
	120	36.6	55	224	[a,b]	
	140	42.7	36	127[b]	[a,b]	[a,b]
	160	48.8	22	45	240[b]	240[b]
	180	54.9	12	29	168[b]	180[b]
	200	60.1	8	22	47[b]	120[b]
	220	67.1	6[b]	17[b]	30[b]	80[b]
	240	73.2	5[b]	12[b]	23[b]	60[b]
	250	76.2	0	10[b]	20[b]	51[b]

Source: Data from J. Miller, ed., 1979, *NOAA Diving Manual: Diving for Science and Technology*, 2nd ed., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Govt. Printing Office, Washington, D.C. (Excursion times are based on oxygen tolerance limits in the U.S. Navy Diving Manual (1973) Change 1, Table 13-1.)

[a] = Unlimited excursion time.

[b] = Excursion times involving exceptional oxygen exposures.

While excursion diving during open-sea habitat programs primarily has been done on a no-decompression basis, the laboratory studies described and the few open-sea decompression excursion dives made, clearly show the advantages to be gained when decompression excursions are used, as has been the case commercially with helium-oxygen breathing mixtures. Comparable procedures need to be developed and tested further for nitrogen-oxygen breathing mixtures.

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Chapter 9

Habitats Around the World

The habitat programs described in the previous eight chapters constitute the major efforts devoted to seafloor habitation and exploration since 1962. In some of these programs, the same habitat was used repeatedly over a period of years; in others, the habitat was used for only a single saturation dive or a series of dives over a few months. In addition to these projects, many of them highly publicized, there were numerous programs known only to those involved or on a regional basis. This chapter presents an overview of these lesser-known but often equally interesting programs.

A review of the undersea habitat programs conducted throughout the world reveals that most succeeded or failed as a result of the efforts of a comparatively small group of dedicated individuals rather than large official groups or organizations. Several of the programs in Eastern Europe were developed and implemented by sport diving clubs, sometimes at considerable financial and personal risk. In the United States, several habitats were constructed at universities as part of student engineering projects. More often than not, the programs were underfunded and understaffed, which usually required makeshift arrangements and frequent compromises with engineering principles, and in some cases, good safety practices.

Habitats have been made from a variety of discarded or available pieces of equipment. We already have learned of the ill-fated HUNUC

habitat made in South Africa from two molasses crystallizers. The Kitjesch habitat built in the Soviet Union was a modified railroad tank car whose major alteration was cutting holes for the ports. Klobouk, built in Czechoslovakia, was created simply by turning an industrial cauldron upside down, and Suny-Lab in the United States was made from a used cement mixer. It is ironic to find that during the same period that nations were spending billions to send men to the moon, such primitive equipment was being used to explore the vast new world of the oceans.

Adventure in many of these programs often came in unanticipated quantities, with the common thread being the incredible bad luck experienced due to adverse weather conditions. Time after time, storms arose unexpectedly, resulting in delays, aborted plans, destruction of a habitat, or herculean efforts by the surface-support team to keep things going. Bad weather seemed to be the rule, not the exception. Ironically the aquanauts often had it easier than the surface-support team. On many occasions, the aquanauts were snuggled serenely in their habitat on the bottom while their colleagues were battling the elements on the surface.

ADELAIDE

Australia, 1967-1968

A newspaper report in September 1967 briefly described an Australian habitat. According to this report, the habitat included living and sleeping accommodations, and a laboratory facility with equipment for recording noises made by fish. The habitat, made from pontoons, evidently had some capability for decompression, and was capable of supporting a crew for several weeks in relative comfort. Several persons are purported to have dived in it.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Adelaide	Australia	1967-1968	-	-	-	14+	-	-	-	Ship raft	-	-	From pontoons

ASTERIA



Italy, 1971

In 1971, the relatively unpublicized habitat Asteria was completed (Fig. 9-1). Built by Ditta Roberto Galeazzi S.p.A. in La Spezia, Italy, it was to be used as a diving training facility in Lake Garda near Brescia in northern Italy for the A. Rossi Technical Institute in Virenza.

The overall height of the habitat was 18.4 feet (5.6 m), including the 4.9-foot (1.5 m) high tripod legs used to support it on the seafloor. Because of the unusual shape, the diameter varied from the 5.9-foot (1.8 m) lower section to a width of 9.8 feet (3.0 m) for the upper section. This larger section was designed as a pressure vessel and served as the decompression chamber. It contained folding cots and seats, a work bench, lights, and the other necessities for seafloor living, including an environmental control center. The upper compartment also included a 2.0-foot (0.6 m) hatch leading to a 3.3 × 3.9-foot (1.0 × 1.2 m) capsule presumably used for ascent to the surface in the event of an emergency evacuation (not shown in Fig. 9-1).

The lower section included the main entrance, the diving area, a second environmental control center, and a 2.0-foot (0.6 m) diameter upper and lower hatch, each with a small viewing port in the center. Both upper and lower compartments contained internal and external communication systems. Asteria incorporated a total of five 9.8-inch (0.25 m) ports, including one facing upward. Asteria could be used to depths of 164 feet (50 m). Although air normally was used as the breathing gas, it also was possible to use helium-oxygen mixtures.

For emplacement, a large rectangular anchor base containing three pulleys was placed on the seafloor. A counterweight system, controlled from inside the habitat, was used whereby the habitat was lowered by pumping the water out of a large ballast tank located on the seafloor attached to a line passing through the pulleys. As the positive buoyancy of the ballast tank increased, it rose to the surface, which in turn pulled the habitat downward. The process was reversed to return Asteria to the surface. A flag and a light attached to the ballast tank served as a beacon while the tank was on the surface. Once submerged, Asteria was supported

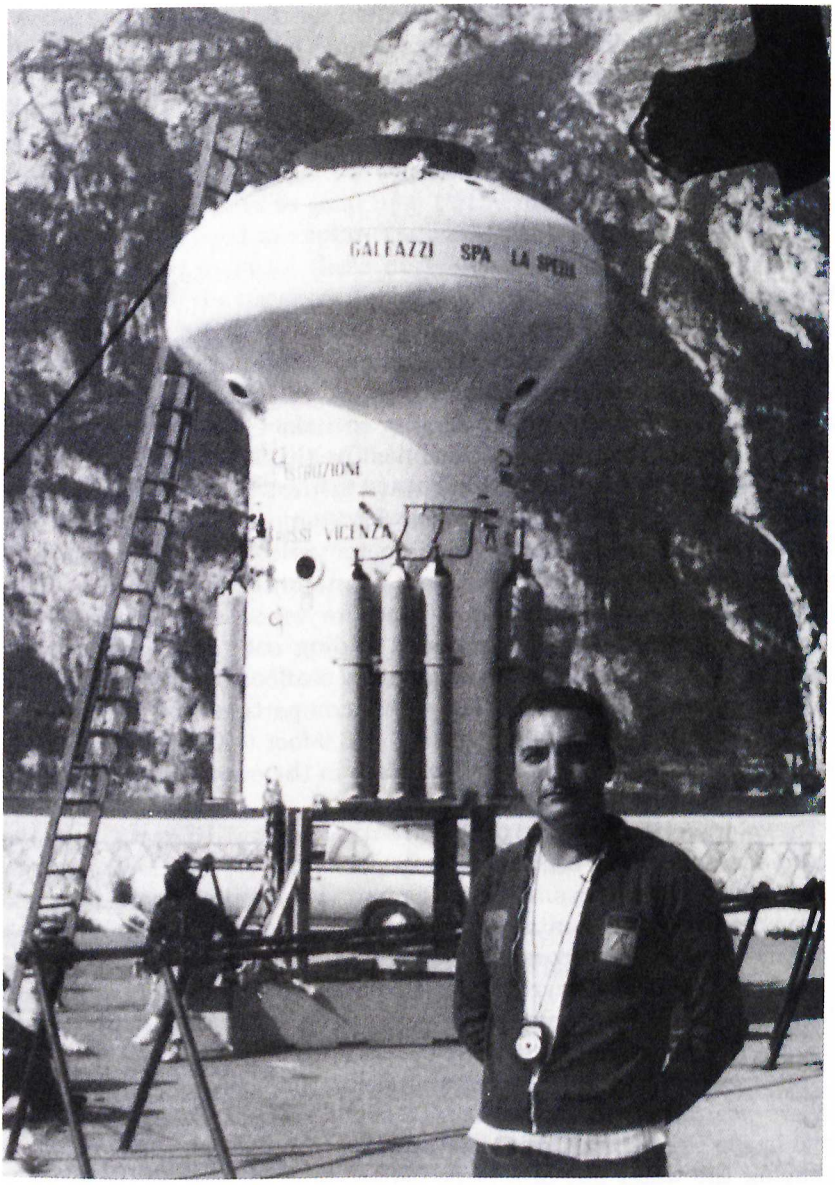
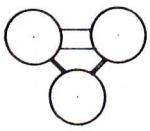


Figure 9-1. Asteria. *(Courtesy of Ditta Roberto Galeazzi. S.P.A., La Spezia, Italy.)*

from the surface by a specially equipped barge. Available information at the time of publication did not reveal the extent to which this habitat was used. Asteria is still located at the A. Rossi Technical Institute in Vicenza (Bartolli, Pers. Commun.).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Asteria	Italy	1971	Lake Garda	50	-	-	H=5.6 W=1.8 3.0	-	Air He/O_2	-	-	-	Diver training, instrument testing

ATLANTIK



Italy, 1969

In January 1969, a habitat program was undertaken in Italy. It was referred to as Operation Atlantide and sponsored by the Association of Cavern Explorers. The impetus for the effort came from the sport diving community. The location of this relatively unknown program was Lake Cavazzo, 18.6 miles (30 km) north of Udine, the capital city of the northern Italian region of Frianul. Construction of Atlantik began in January 1969 under the direction of the program's organizer, Luciano Meccarozzi. One of the primary goals of the program was to test-mass-produced pressure chambers for use as future undersea habitats.

The Atlantide operation used three interconnecting steel pressure cylinders 23 feet (7 m) long and 6.6 feet (2 m) in diameter, each with a displacement of 44 tons. The three cylinders were connected by steel cables. Two of the cylinders were connected by a trunk, permitting the aquanauts to move freely from one to the other. One cylinder was used for ballast. The second served as a machine room and contained two air compressors, a generator, two snorkels to the surface, and a seafloor-to-surface communication and television system. The third cylinder was the living room and appears to have been connected to the machine room. It had an opening at each end, a 6.6-foot (2 m) wet room, and a decompression chamber at one end. The large adjoining room contained four cots, chairs, and a table.

This triad of habitats was placed in Lake Cavazzo at a depth of 39.4 feet

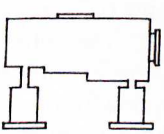
(12 m), although the pressure cylinders were designed to withstand 295 feet (90 m) of pressure. The surrounding water temperature was a cool 60.8°F (16°C), with visibility being very limited. Air was used as a breathing gas, with the compressor located in the habitat's machine room—thus the need for the two snorkels to the surface. To the best of our knowledge, this marks the only occasion on which the primary compressor was located on the seafloor during a habitat program. The reason was to preclude interruption of the air supply in the event of a storm.

It appears that the Atlantik habitat(s) was used for only one series of missions, September 5 to 30, 1969. It was reported that 12 aquanauts lived in the habitat during this period, including 17-year-old Silvana Polese, the fourth woman in the world to become an aquanaut, being preceded only by Madame Cousteau who stayed in Conshelf II in 1964, and the two Soviet aquanauts Maria Barats and Galina Guseva who participated in the 1967 Ikhtiandr program. During Operation Atlantide, the aquanauts were examined daily by a physician. Apparently no medical difficulties were experienced.

Meccarozzi reported that the 3-week program was a complete success. Whether the habitats ever were mass produced, is not known, although the tent village on shore used as a support base was to have been employed as a training center for club aquanauts (Huber, 1970).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Atlantik	Italy	1969	Lake Cavazzo	12	4	-	L=7 W=2	44 Displ. each	Air	Shore	-	-	3 Separate habitats Primary compressor located on seafloor

BAH-I
(BIOLOGISCHEN ANSTALT HELGOLAND)



Federal Republic of Germany, 1968–1969

BAH-I was designed and built by Deutsche Babcock and Wilcox AG as a minimum-cost mobile underwater workman's hut (Walther, n.d.).

Constructed in 1968, it was first tried out in the Flensburg Fjord in cooperation with the Biological Institute, Helgoland, and was West Germany's first habitat.

BAH-I was a horizontal cylinder 6.6 × 19.7 feet (2 × 6 m) mounted on four legs with a ballast tank on each end. The living quarters included a wet and a dry compartment. The dry compartment contained the necessary amenities, including beds, tables, heater, and hot plate. The wet room contained a toilet, the life-support system, water storage, the entrance hatch, and a hatch at the top for entrance on the surface. BAH-I was well heated and insulated on the inside and was coated with a special antifouling paint on the outside. The life-support system included a CO_2 scrubber, a dehumidifier, and an oxygen partial pressure gauge. The legs were bolted in place to facilitate rail and truck transportation. The total weight of the habitat was 20 tons.

The habitat was launched in the Port of Kiel in mid-September 1968. On September 19 it was towed to Flensburg Fjord, where it was emplaced on the floor of the Baltic the next day at a depth of 32.8 feet (10 m) and connected to the surface-support ship (Dorschel, 1970). The first mission lasted for 11 days, during which the two aquanauts, Dr. Jurgen Dorschel and Dr. Gerhard Lauckner, conducted a number of seafloor observations and studies. Bad weather seriously complicated the work on the surface but left the habitat and aquanauts unscathed. The breathing gas used during the 10-day saturation was a nitrogen-oxygen mixture in which the oxygen partial pressure was maintained at about 0.25. At the end of the mission, the habitat was raised to the surface, towed to shore, and transported back to the factory in Oberhausen. The project was marred by the death of Dr. Horst Hartmann who was to have been the medical supervisor on board the support ship *Friedrich Heinke.* He died during a reconnaissance dive without ever having entered the habitat (Haux, 1969).

After some modification during the winter, which included addition of a turret hatch and a new gas supply system, the habitat was transported to Lake Constance in June 1969 and towed to the site near Sipplingen by a local excursion ship. Figure 9-2 shows the modified habitat. After a week's operation at shallow depths, during which the support systems were tested, heavy anchors were placed on the lake bottom and the habitat ballasted and lowered. It was occupied for 1 week by two divers and then returned to the surface. During a later attempt to place the habitat at a depth of about 154 feet (47 m) for the next mission, the habitat partially flooded and sank to the muddy lake bottom with two men inside. It was decided to blow the water out, which required that the

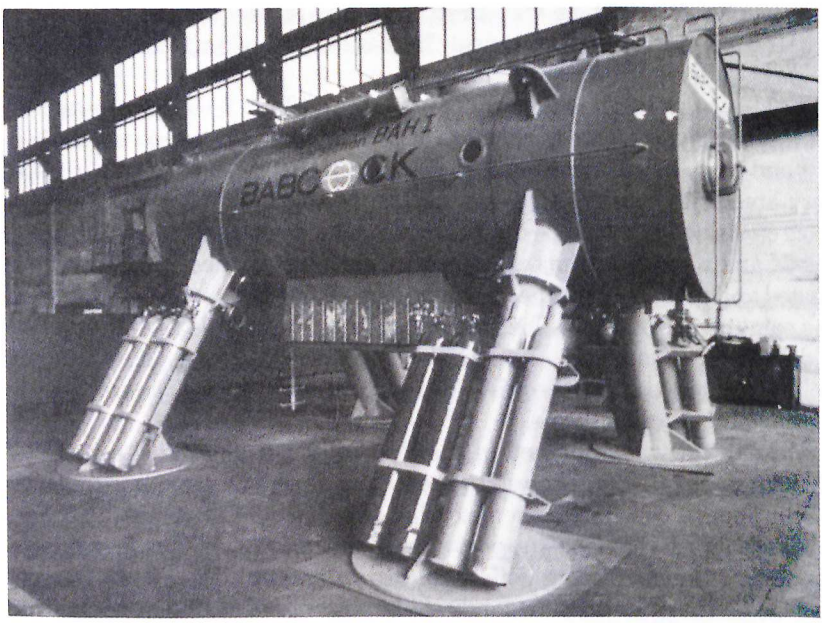


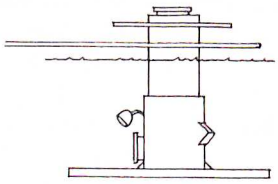
Figure 9-2. BAH-I, *(Courtesy of Deutsche Babcock and Wilcox, A.G.. Oberhausen, Federal Republic of Germany.)*

men remain inside. The habitat then was returned slowly to the surface, with the men still in it, at a rate that allowed safe decompression. Afterward the habitat was examined on land and put back in the water for several months of unmanned tests prior to its return to Oberhausen.

The habitat never was used again. In June 1980 at a special dedication ceremony, BAH-I was placed by Deutsche Babcock AG in front of the Institute for Geology at the Technical University of Clausthal-Zellerfeld, where it remains as a reminder of an earlier age of undersea exploration (Tekacz, pers. commun.).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
BAH-I	Federal Republic of Germany	1968–1969	Baltic	10	2	11	L=6 D=2	20	N_2/O_2	Ship	Readily movable	-	-

BALANUS



Soviet Union, 1968

This habitat (its name means "barnacle") was designed as a stationary underwater observation chamber and apparently was not used as an ambient pressure system. It was sponsored by the Far Eastern Branch of

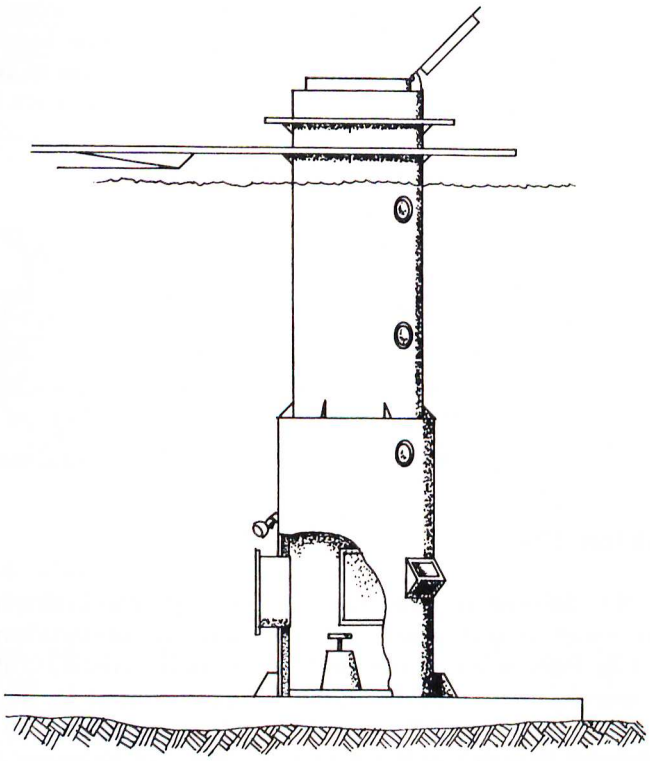


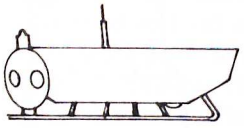
Figure 9-3. Balanus. *(From A. Lebedew, 1969, Balanus, Poseidon* ***8****(92):350.)*

the Soviet Academy of Sciences and was developed by Victor Waskowski. Balanus was a 5-ton vertical cylinder with an overall height of 18 feet (5.5 m) designed to sit on the bottom at a depth of 16.4 feet (5 m). The entrance was on top, as the upper portion of the chamber protruded from the water (Fig. 9-3). The observation chamber, 4 feet (1.2 m) in diameter and about 8 feet (2.5 m) high, contained several observation ports.

Balanus was used in 1968 in Posjot Bay off the Gamowa Peninsula in the Japanese Sea. The general purpose was to facilitate the study of local marine life, which in that area was considered to be similar to marine life in arctic waters. Balanus contained two compressors to supply air to divers operating outside, who swam about using air hoses attached to the habitat. Equipment inside included a suction pump to aid in the collection of artifacts and other scientific support equipment (Lebedew, 1969).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Balanus	USSR	1968	Japanese Sea	5	-	-	H=5.5 D=1.2	5	Air	Shore	-	-	Observation chamber

BENTOS-300



Soviet Union, 1966–

Bentos-300 is different from any other habitat described in this book—it can move under its own power. The program was undertaken at the request of the Polar Scientific Research and Planning Institute of Fisheries and Oceanography under the general supervision of O. N. Kiselev. Plans for it were revealed at the April 6-11, 1966, meeting of the Section for Underwater Research of the Soviet Academy of Sciences' Oceanographic Commission. The overall objective of the program was to develop an oceanographic research facility with special emphasis on the study of

ogical organisms, especially fish. Of particular interest was the study rtificial schooling of fish and the development of netless catching hniques; thus the habitat was to be equipped with a system of local d generators for producing light, sound, electric, magnetic, and other ysical fields (Boylan, 1974).

The Bentos-300 was designed as a diver lockout submersible-habitat ig. 9-4). Plans called for the overall length to be 68.9 feet (21 m), a beam 18.0 feet (5.5 m), and a height of 36.7 feet (11.2 m). While the original esign called for a crew of 10 to depths up to 984 feet (300 m) for periods of 5 days, a 1976 article in *Pravda* stated that "the 30-meter submersible is apable of autonomous operation for about two weeks. It will carry a crew f 30 men" (Anon., 1976*a*).

The most recent information (Chuba, 1981) reveals that the completed Bentos-300 is a 500-ton vehicle with a crew of 24 and a capability of operating independently underwater for 14 days. The steel pressure hull is externally ring stiffened, with elliptical bow and stern bulkheads. Ballast tanks, trim tanks, high-pressure air tanks, and other equipment are mounted between the pressure hull and the outer hull. The habitat is equipped to support divers at depths of 656 feet (200 m), and the life-support system includes helium-oxygen breathing equipment, and air.

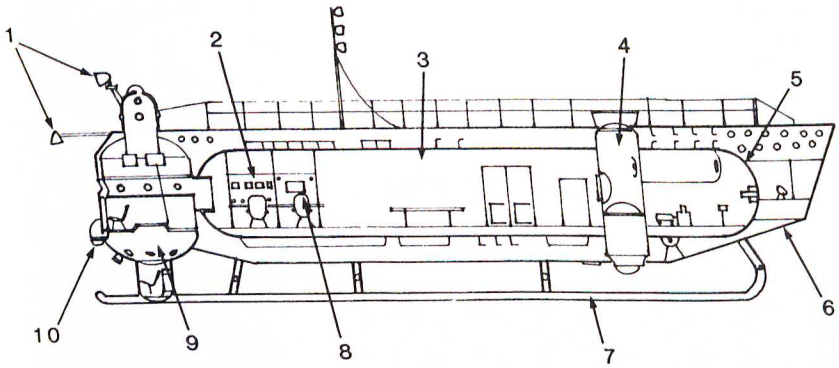


Figure 9-4. Schematic of early Bentos-300 design. (From Boylan, L. 1974, Underwater Activities in the Soviet Union, Informatics Inc., Rockville, Md., 57.)

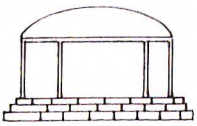
1. Rotating and extendable illuminators
2. Control console and research instrumentation compartment
3. Crew quarters
4. Diver access trunk and lock
5. Cylindrical steel pressure hull
6. Ballast tanks and outboard equipment stowage space
7. Skids
8. Instrument displays
9. Observation chamber
10. Propulsion unit

Other systems provide extensive communication flexibility to surface buoys, support vessels, and shore stations. In the event of an emergency, the entire crew can ascend to the surface in an escape chamber, which doubles as a navigating bridge during towing and an observation chamber when submerged. The propulsion system is a pod of storage batteries that can propel the habitat at speeds of 1.5 knots submerged. Scientific equipment includes oceanographic instrumentation, special illumination systems, telescopes, photographic and television equipment, and a darkroom.

Details of the final configuration of Bentos-300 have not been released by the Soviets. Whether the habitat is 98.4 feet (30 m) as recently reported or 68.9 feet (21 m) as planned originally is not known. Similarly, a recent report states that the depth capability is 1312 feet (400 m) instead of the originally planned 984 feet (300 m). Regardless of the final configuration, apparently the habitat required about 10 years to develop. It was reported in 1977 that Bentos-300 was about to depart from Sevastopol for its first operational trial run in the Black Sea and that a large program of hydrological scientific research had been planned (Zotiyev, 1977). This habitat clearly represents an advance over the sessile habitats reported throughout the rest of this book.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Bentos-300	USSR	1966	Sevastopol	300	24	14	L=21 W=5.5 H=11.2	500	Air He/O_2	Ship buoy	Self-propelled	-	Only self-propelled habitat

BUBBLE



Great Britain, 1966

In 1965 the Royal Engineers Diving Establishment was asked to provide a centerpiece for the swimming pool display at the International Boat Show in Earl's Court, London. The *Daily Express,* which sponsored the show, built a clear plastic cylinder, named the Bubble Habitat, to demonstrate underwater living. During the 2-week show, personnel from the Royal Engineers Diving School manned the Bubble. Following the show, the engineers were rewarded for their efforts by gaining possession of the Bubble.

Using the Bubble for an actual undersea experiment was initiated at the Royal Military Academy, Sandhurst, in cooperation with the Royal Engineers. The objective was to provide a summer diving expedition for a party of cadets and to study the bends threshold for the Royal Navy. More specifically, the investigators wanted to know if divers could come to the surface without any decompression after becoming saturated at a depth of 31 feet (9.4 m) (Jones, Owens, and Crawford, 1966).

After a survey of possible sites, it was decided that the experiment could best be carried out in the Maltese Islands. The site selected was on the northeast corner of a small, bare, uninhabited island named Cominotto located just off the larger island of Comino. The expedition party was composed of fifteen Sandhurst cadets, six officers, and six supporting staff. The project was named Exercise Sea Snail.

The Bubble habitat (Fig. 9-5) basically was a Perspex cylinder 7 feet (2.1 m) in diameter, with a domed top and an open bottom similar in some respects to the Sub-Igloo habitat used in the Canadian arctic some years later. The Perspex cylinder was placed in a free-standing metal floor frame, covered with glass-reinforced plastic, and provided with an entry. This structure was held in position 3 feet (0.9 m) above the seabed by

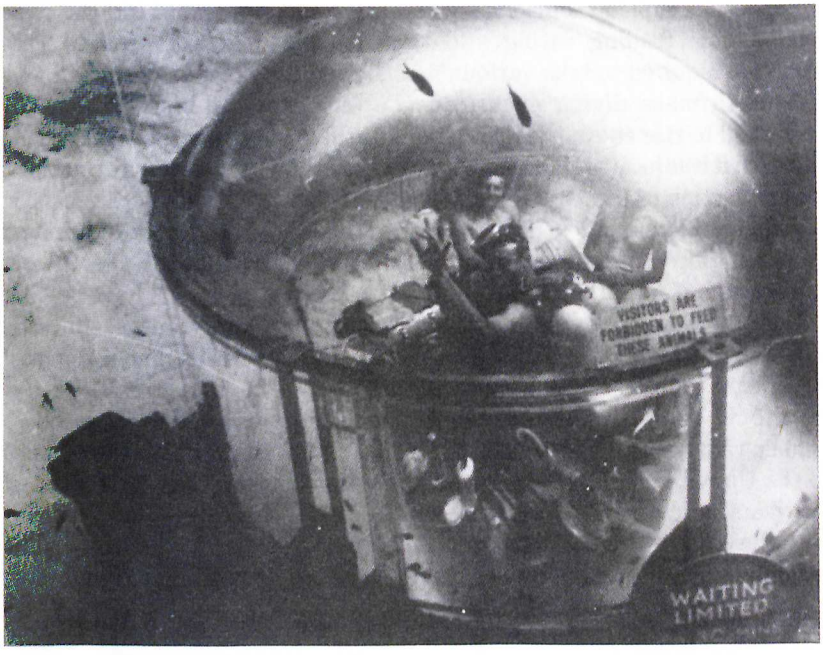


Figure 9-5. Bubble. *(Courtesy of Royal Engineers Diving Establishment, Southampton, England.)*

means of six tubular metal legs bolted to a metal ring fixed around the Perspex at the junction of the wall with the dome. Eight tons of pig iron ballast were placed on the base of the legs to achieve the necessary negative buoyancy. The habitat was transported in pieces and assembled at the operational site. Bubble was equipped with a telephone to shore, lights, and a valve to control the flow of air from the shore-based compressor. Food was supplied in plastic containers by divers from the surface.

The habitat was placed at a depth of 34 feet (10.4 m), which resulted in a saturation depth of 31 feet (9.4 m). As with most other habitats, the humidity was high, hovering around 100%. The surrounding water temperature was 75°F (23.9°C), resulting in an inside temperature of about 78°F (25.6°C) at night and 85°F (29.4°C) during the day. Visibility was 150 feet (43.7 m). The breathing gas, air, was circulated continuously through the habitat so that a CO_2 removal system was not required. Frequent air samples were obtained and checked to ensure that CO_2 levels were safe.

The Bubble was occupied by two or three aquanauts at a time. During the Sea Snail expedition, seven 12-hour and two 24-hour saturation missions were conducted. Medical examinations were administered before and after each saturation exposure. During the stay on the bottom, the aquanauts occupied themselves watching and photographing the scene around them, reading, eating, and receiving the inevitable visitors. They also were required to take various aptitude and dexterity tests and were allowed to make diving excursions outside the Bubble but were not permitted to rise above the lip of the habitat or to leave the level plateau on which it was located. Most aquanauts made at least two such excursions. On completion of the 12- or 24-hour saturation exposure on the seafloor, the aquanauts ascended to the surface at a controlled rate requiring 2 minutes. Decompression sickness was encountered after the 24-hour exposures but not after the 12-hour saturations.

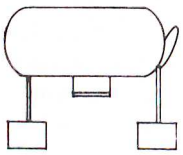
Exercise Sea Snail was considered to be completely successful; over 180 hours were spent in Bubble on the seafloor. Perhaps one of the most significant findings was that one cannot saturate at a depth of 31 feet (9.4 m) and return to the surface without the danger of bends.

Following the completion of Exercise Sea Snail, the habitat was returned to the United Kingdom, where it has been used sparingly over the past few years. It is now at the Underwater Training Center in Fort Williams, with the hope that it may be used as a control base for the recovery of the famous wreck, the *Mary Rose* (Chitty, pers. commun.).



NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Bubble	U.K.	1966	Malta	10	2-3	1	D=2.1 sphere	8 Bal.	Air	Shore	Readily movable	0	Decompression experiments

CARIBE-I (KARIBE)



Czechoslovakia and Cuba, 1966

Pursuant to an agreement between the Czechoslovakian Academy of Sciences and the Institute of Oceanology of the Republic of Cuba, this first Soviet bloc habitat was brought to Cuba in June 1966 by a 7-man contingent from Czechoslovakia headed by Josef Mergl (Fuentes, 1966).

The completed steel habitat was emplaced at a depth of 65.6 feet (20 m), where it remained from July 17 to 21, 1966, in the cove of Rincon de Guanabo, about 18.6 miles (30 km) east of Havana. It was held down by chains attached to four railroad wheels and two tracks, which provided the needed 6 tons of ballast (Fig. 9-6). The two-man habitat contained two

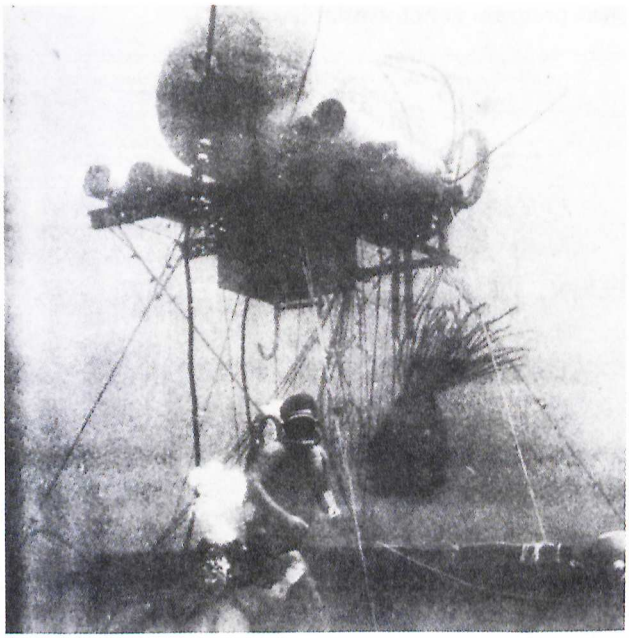


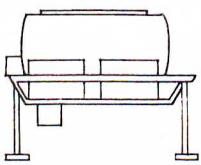
Figure 9-6. Caribe-I. *(From N. Fuentes, 1966, Operation Caribe-I, Living in Another World, Cuba, Sept., p. 24.)*

small ports on each end and a large port on one side. Its overall size was 4.9 × 11.5 feet (1.5 × 3.5 m) (Diomidov and Dmitriyev, 1969). The diver entrance trunk, equipped with a ladder, was located 16.4 feet (5 m) above the bottom. Equipment in the habitat included electric lights, French-made communication equipment, including a bullhorn for underwater talking, and a telephone. While no mention was made of heating, the inside temperature was maintained between 75° and 86°F (24° to 30°C) throughout the mission. Air was used as the breathing gas with life support provided from three surface-support vessels (Diomidov and Dmitriyev, 1969).

The purpose of Caribe-I was to test human reaction to underwater living, photography, and specimen collection. Two aquanauts, Norberto Ruentes (age 23) and Alberto Korda (age 40) spent 80 hours underwater, making three excursions daily to a depth of 115 feet (35 m) (Fuentes, 1966). A 1969 article by Diomidov lists the names of the aquanauts as Czechoslovakian Iozef Morchel' and Cuban Michael Mortans'ye. During the first night, the Cubans aboard the military underwater-ship 012 laughed a good deal when the North American radio announced with concern: "Havana, July 17, A group of Czech military technicians began investigations today in order to install for the Cubans presumed submarine rocket launchers" (Fuentes, 1966, p. 23). Further information on this early habitat program is not available.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Caribe-1	Cuba-Czech	1966	Rincon de Guanabo near Havana	20	2	3	L=3.5 D=1.5	6 Bal.	Air	Ship	Readily movable	-	First Eastern Bloc habitat

EDALHAB
(ENGINEERING DESIGN AND ANALYSIS LABORATORY HABITAT)



United States, 1968–1972

This small habitat was designed and built as an engineering project by students from the University of New Hampshire under the direction of Dr. Godfrey H. Savage. It was constructed mainly of salvaged and

donated materials. The one-room living area was enclosed in an 8 × 12 foot (2.4 × 3.6 m) cylinder with a small viewing port at each end (Fig. 9-7). The interior was insulated with 1½-inch (3.8 cm) thick unicellular foam. Entry was made through a hatch centrally located in the floor. The interior had two permanent bunks (which folded to form a large seat) and a collapsible canvas cot. Communications, air, and power were provided from the support ship or shore to the habitat through umbilicals. Edalhab, which had no specific facilities for scientific investigation, was not moved easily from site to site (University of New Hampshire, 1972).

Edalhab was first tested in Alton's Bay off the coast of New Hampshire in 1968. It was used subsequently for two other missions in the same general area near the Isle of Shoals at depths of about 40 feet (12.2 m). In January 1972, Edalhab was emplaced at a depth of 45 feet (13.7 m) at three different sites off the coast of Miami, Florida, as the primary habitat for project FLARE (Florida Aquanaut Research Expedition), sponsored by the NOAA with the cooperation of the University of New Hampshire and the Woods Hole Oceanographic Institution. The habitat was modified to make it compatible with the surface-support ship *LULU*, which normally was used to support the famous research submersible

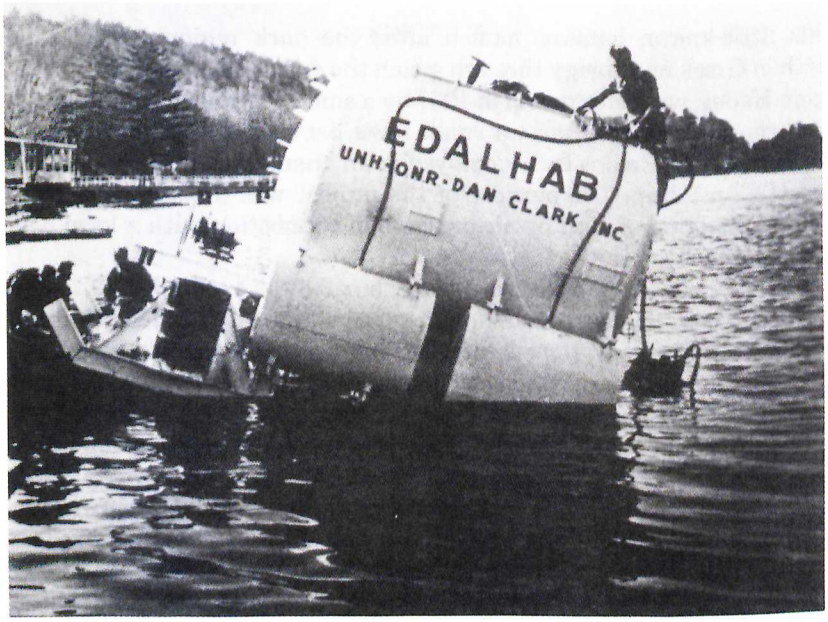


Figure 9-7. Edalhab. *(Courtesy of University of New Hampshire, Durham, New Hampshire.)*

Alvin (Fig. 6-12). This modification increased the weight of the habitat from 14 to 25 tons.

During the FLARE program, twenty-five aquanauts lived in Edalhab for five days each, in teams of three. A wide variety of marine biological and geological studies were carried out during the three-month program. After each mission, the aquanauts swam to the surface and entered a deck DDC located on board *LULU* for the 19-hour decompression.

Edalhab has not been used since the FLARE program and currently is located on a dock in Woods Hole, Massachusetts.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Edalhab	U.S.A.	1968 1972	Alton's Bay, N.H.; Miami, Fla.	12.2 13.7	3	3–5	L=3.6 D=2.4	14 25	Air	Shore ship	Readily movable	19	-

EREBOS

Czechoslovakia 1967–1968

This little-known habitat, named after the dark region beneath the earth in Greek mythology through which the dead must pass before they reach Hades, was constructed in 1967 by a small group of amateur divers from the vicinity of Olsany, a small town between Pilsen and Prague. Plans called for Erebos to be deployed in an abandoned quarry about 65 feet (19.8 m) deep. The purpose of the project was to test methods of suction dredging of mud by air pressure in connection with a local dam construction project.

The habitat itself was basically a steel box $8.8 \times 4.4 \times 5.9$ feet ($2.7 \times 1.3 \times 1.8$ m) containing six round, double-glass view ports 15 inches (38 cm) in diameter. It was equipped with two bunks and a small table. Additional bunks, electricity, and a telephone were planned for 1968. It was estimated that the habitat would require about 15 tons of ballast.

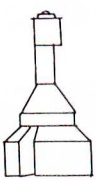
The story of the deployment of Erebos is an example of determination conquering adversity. Since the divers could work only on weekends, work went slowly. A 22-ton concrete slab located only 164 feet (50 m) from the quarry took 4 months to get into the water. After this, heavy chain was attached to the slab to moor the habitat at the desired depth of 37.7 feet (11.5 m). The support ships were two rubber rafts, with the habitat located in between. The positive buoyancy of Erebos was 6 tons.

The habitat was flooded and winched down using a chain windlass. On the first attempt, the chain broke and had to be repaired. The next day it

was fixed and the habitat lowered to the 65-foot (20 m) bottom. Compressed air was added to raise the habitat to the desired depth. Because of over-pressurization, a port broke, and the habitat sank to the bottom and filled with mud and water. A rubber raft was weighted with lead, lowered to the bottom, and stuffed in Erebos, where it again was inflated in an attempt to raise the habitat. Because it was now Sunday night, the operation was put off until the following weekend. A new view port was made, but on returning to the quarry, divers found that the rubber raft had sprung a leak, and the process had to be repeated. Finally the habitat was moored successfully at the desired depth. There is no additional information as to the extent to which the habitat was used except that it was first deployed in 1967 and apparently used again in 1968 (Tauber, 1968). In retrospect, it would seem that with all the trouble it had, the name of the habitat was appropriate.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Erebos	Czech	1967-1968	Olsany	11.5	2	-	L=2.7 W=1.3 H=1.8	15 Bal.	Air	Shore	Readily movable	-	Deployed in quarry

GEONUR



Poland, 1975–1980

Geonur ("geological diver") is described as a four-man habitat capable of several days' stay at depths up to 164 feet (50 m). It was designed by Antoni Debski who earlier had designed and built Meduza-I at the Gdynia shipyard in Poland. The habitat contains a working compartment, a large trunk, and a decompression chamber (Fig. 9-8) (Anon., 1975). The overall height of Geonur is 24.9 feet (7.6 m) and the width at the base 13.8 feet (4.2 m). Breathing gas is supplied from a support vessel, although the habitat contains a 30-hour independent life-support system (Anon., 1976*b*). Geonur is equipped to perform rescue, construction, and repair operations, as well as to support marine biological, geological, archeological, and physiological research.

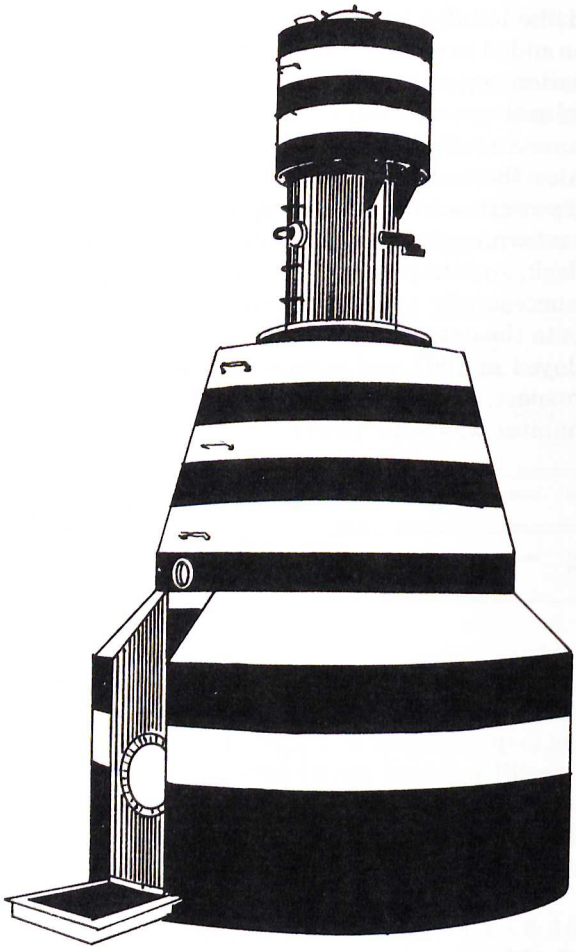


Figure 9-8. Geonur. *(From Anonymous, 1975, Polish Underwater Drill Rig, Morze 5:33.)*

The primary missions cited for the habitat are geological in nature, such as the study of the seafloor and the search for minerals (Nowak and Juszczak, 1977). For these roles, Geonur is equipped to drill bore holes up to 328 feet (100 m) deep. The system has been tested at sea in winds up to 26 knots. The Geonur "Swimming Drill" is the first of its type in Eastern Europe. It has made numerous underwater probes, mainly in ports, shipyards, and shipping lanes. In 1976 Geonur made it possible to

penetrate the wreck of the German transport ship *William Gustloff* (Anon., 1977).

In the summer of 1980, Geonur was put on board a ship bound for Senegal on the west coast of Africa. The plan was to use it for drilling and coring operations in the Atlantic Ocean in preparation for construction of approaches to the fishing port of St. Louis. Twenty days after being moored at the construction site, before work had begun, the habitat was driven ashore by waves and damaged so severely that it was abandoned on the Senegal coast. The insurance money received by the Polish Society of the Friends of the Earth Sciences was used to begin construction of Geonur-II.

Plans call for Geonur-II to serve as an underwater base for diving; drilling; inspection of moorings, cables, and underwater structures in Polish harbors; and as an observation platform from which to collect data on the marine environment (Anon., 1982). Genour-II also will be used to map bottom mineral deposits in the south Baltic.

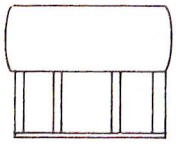
The habitat will be a vertically oriented structure that achieves stability due to its fairly deep draft in much the same manner as does the Floating Instrument Platform (FLIP) described in Chapter 10. Genour-II is to have two hulls, with the space between filled with 28 tons of water. Four trim tanks located in the base further increase stability when the habitat is anchored to the seafloor. The inner (pressure) hull is divided into a living area, engine room, work area, diver lockout room, and decompression chamber. The self-propelled habitat can accommodate up to eight persons and has maximum diving depth of 492 feet (150 m). Either compressed air or helium-oxygen mixtures can be used as breathing gases. Sufficient supplies are on board to support four persons for 7 days.

Drilling into the seafloor from Genour-II can be carried out to depths of 262 feet (80 m). The real innovation, however, which is being patented, is a drilling probe of a completely new type, capable of taking unbroken core samples from a depth of 393 feet (120 m) below the seabed. Because of the deep draft of the habitat, however, the shallowest water in which drilling operations can be conducted is between 39.4 and 59 feet (12 to 18 m). Soil samples are analyzed in the on-board laboratory.

Geonur-II represents a new dimension for an undersea habitat by combining diving and drilling operations.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Geonur	Poland	1975–1980	Gdynia	50	4	–	H=7.6 W=4.2	34	–	Ship	Towable	–	For geology

GLAUCUS



Great Britain, 1965

This two-man habitat, named after the mythical Greek diver who dived into the sea and found he had become a deity, was designed at the Bournemouth branch of the British Sub-Aqua Club. The design called for maintaining two aquanauts at a depth of 35 feet (10.7 m) for 7 days. The cylinder was 12 × 7 feet (3.6 × 2.1 m) and stood 12 feet high when mounted on the supporting legs (Fig. 9-9). It had three small ports and contained two bunks and the other necessary amenities, including a toilet with a private entrance under the habitat. Open trays containing soda lime were used to absorb CO_2. Primary power was supplied from the surface. Regular car batteries stored in the habitat were used for emergency power. Illumination was provided by strategically mounted automobile interior lights and a headlight. Both a telephone and a closed-circuit TV system were installed.

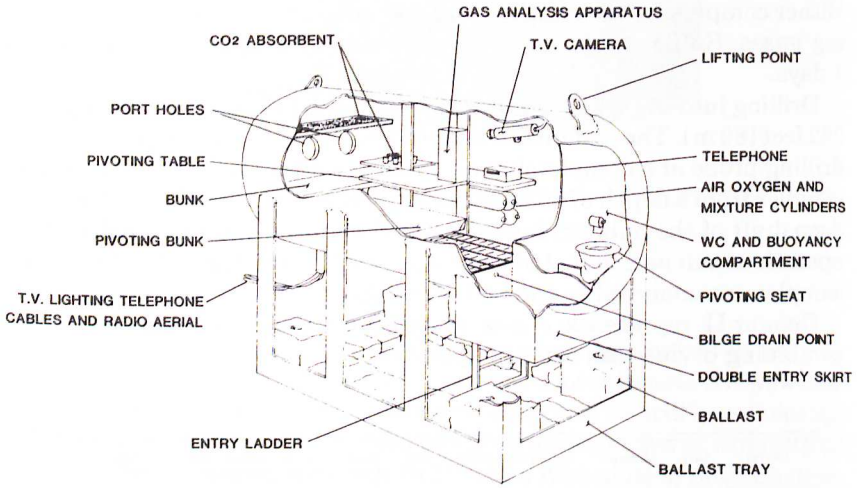


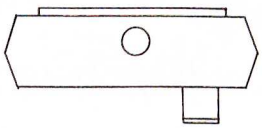
Figure 9-9. Glaucus. *(After C. Irwin and J. Heath, 1966, Glaucus Project Report, p. 3. Courtesy of Bournemouth and Poole Branch, British Sub-Aqua Club, England.)*

Its purposes were to test the aquanauts, equipment, and to conduct simple marine science studies. Following a 19-hour dry run August 27-28, 1965, the habitat was installed near the breakwater fort at Plymouth in the south of England. The depth averaged 35 feet (10.7 m) with a tidal action of plus and minus 5 feet (1.5 m). The 7-day mission began on September 16. Three hot meals were sent down from the surface each day. The primary discomfort suffered by the two aquanauts was the constant need to clear the ears because of 6-inch (15.2 cm) swells in the entrance trunk caused by surge on the surface. Because of the 10 foot tide, the air had to be vented and added accordingly, which also served to reduce any buildup of CO_2.

The program for Glaucus included the testing of two decompression schedules. Decompression was achieved for one aquanaut by breathing air, enriched with an oxygen partial pressure equivalent to an air depth of 25 feet (7.6 m), for 3 hours at a depth of 6 feet (1.8 m). The other aquanaut decompressed by alternately breathing air and 80% oxygen and 20% nitrogen for 3½ hours. Neither aquanaut experienced any symptoms of the bends (Irwin and Heath, 1966).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Glaucus	U.K.	1965	Plymouth	10.7	2	7	W=2.1 L=3.6	13	Air	Shore	Readily movable	3.0-3.5	Decompression experiments

HEBROS



Bulgaria, 1967–1968

On July 16, 1967, one day after the start of the Polish Meduza habitat project, the Bulgarians launched their first habitat program. Hebros-I was placed on the floor of Lake Varna at a depth of 23 feet (7 m). The first two occupants were the inventors, Gere Tomas'yan and Ivan Petrov. The habitat (Fig. 9-10) had been built by a volunteer group called the Marine Club of Plovdiv and was constructed from a locomotive boiler (Miller, 1974). During the final few days of the 7-day saturation, as part of a psychological study, the two aquanauts were isolated from the surface

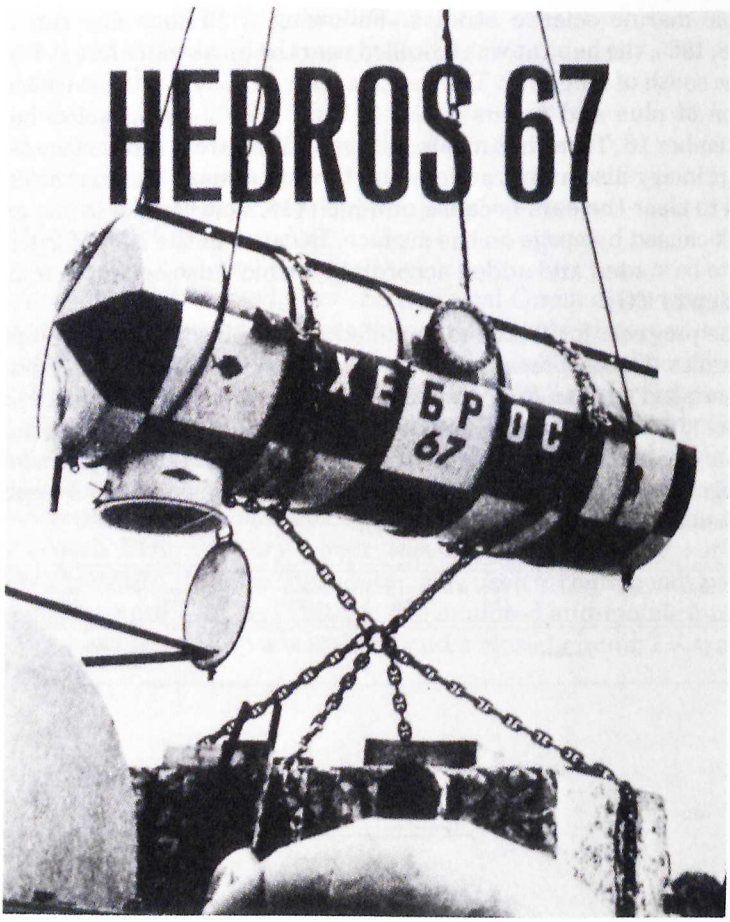


Figure 9-10. Hebros. *(From L. Gurinov, 1968, Khebros-2, Poseidon* ***9:****397.)*

and were forbidden even to see the surface-support divers when they brought food. Communication was kept at a minimum, and during the last 24 hours, all communication to the surface was cut off, as were the lights in the habitat (Podrazhanskiy, Rostarchuk, and Stefanov, 1973).

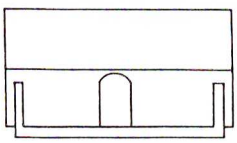
During this mission and the second 7-day, three-man saturation exposure that followed, air supplied from shore was used as the breathing gas. Because of the shallow depth, there was no requirement for decompression at the end of the mission; the aquanauts ascended directly to the

surface. Hebros-I was not used again. To the best of our knowledge, it is still located in the Plovdiv Museum in central Bulgaria.

Hebros-II was built in 1968 and was designed to have an autonomous system for lowering and raising it that could be controlled by the aquanauts. It had a diameter of 8.2 feet (2.5 m) and a diameter of 22 feet (6.7 m). Its original plans called for it to be emplaced at a depth of 98.4 feet (30 m) for a period of 10 days for testing (Gurinov 1968). We do not know the extent to which Hebros-II was used.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Hebros-I (Khebros)	Bulgaria	1967	Lake Varna	7	2	7	L=5.5 D=2.0	-	Air	Shore	Towable	-	Made from a locomotive boiler

HUNUC
(HABITAT UNIVERSITY OF NATAL UNDERWATER CLUB)



South Africa, 1972

HUNUC, South Africa's only habitat, was designed by the Underwater Club of the University of Natal. The shell of the habitat was formed from two obsolete sugar crystallizer vessels donated by a local sugar company (Fig. 5-29). The habitat had two levels (Fig. 9-11), with an overall height of 19.4 feet (5.9 m) and an internal width of 4.9 feet (1.5 m). The lower story normally was flooded and contained the entrance; the upper level was divided into a living compartment and a laboratory and work area. Power and water were supplied from shore. HUNUC, which was not a pressure vessel, was designed to use air as a breathing gas, and canisters containing soda lime were used as a CO_2 scrubber. Designed for four aquanauts, the habitat contained four bunks and the necessary life-support amenities. Because of its height, HUNUC had a very high center of gravity. This feature, when coupled with the fact that it was underballasted, caused serious problems.

The habitat was completed in April 1972 and subjected to 2 weeks of successful trials in Durban Harbor. On May 21, 1972, HUNUC was towed

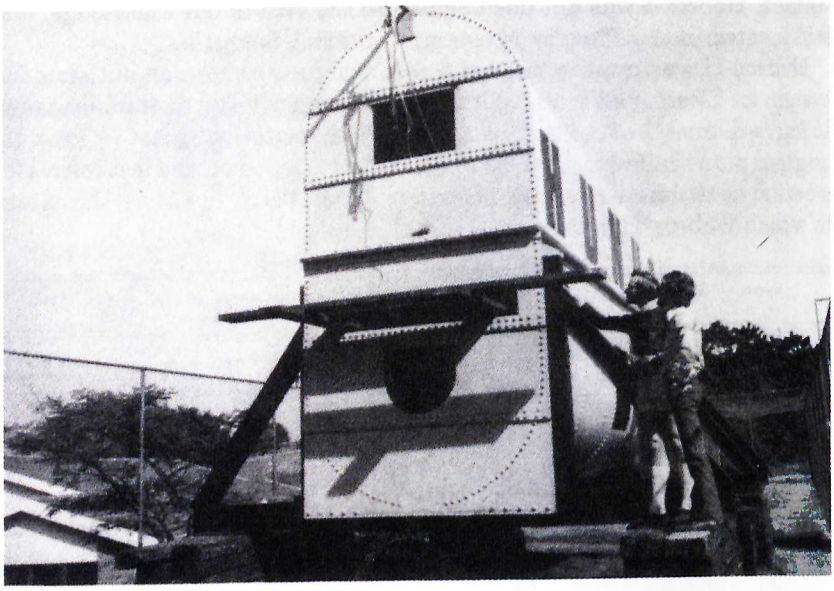


Figure 9-11. HUNUC. *(Courtesy of Oceanographic Research Institute, Durban, South Africa.)*

out to sea by the diving vessel *Fleur* of the South African Navy for what was to be a series of five scientific missions. Heydorn and Addison (1973, pp. 5-6) describe events following the arrival of HUNUC at the dive site:

> Close to the site of submergence, the tow was taken over by two skiboats of the Natal Anti-Shark Measures Board and the habitat was anchored at its selected site without a hitch.
>
> At this stage, two serious problems became evident. There was a two-hour delay in lowering the habitat to the seabed due to difficulties with the underwater winches selected for the purpose. Furthermore, an exceptionally strong ground-swell came up and placed heavy strain on the anchor cables. When the habitat did reach the seabed (by flooding the four buoyancy tanks), darkness overtook the operation and it became impossible to weigh the habitat down with the additional lead ballast waiting on the seabed next to it. Vertical movement of the habitat was violent. Exhausted divers worked until long after dark, but were forced to leave operations until the next morning.

It was discovered the next morning that the anchoring cables had not stood up under the deteriorating conditions, as the habitat had bounced

along the seafloor and come hard-up against Limestone Reef causing extensive damage. The lower portion of the hull had sustained a one-meter long rip and valuable ballast had been lost.

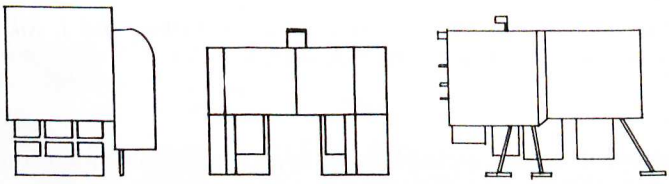
Heydorn and Addison went on to say,

> During the following days, sustained effort eventually led to success in towing the habitat free of the reef and securing it to the seabed closer inshore. The task was completed on 28 May, but by that time fittings of the u/w laboratory, both internally and externally, had to a large extent suffered serious damage. The hull was therefore stripped and all equipment brought ashore for renovation.

The decision was made to abandon the severely damaged hull. The habitat was never used again.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
HUNUC	South Africa	1972	Durban	10	4	N/A	L=5.9 W=1.5	-	Air	Shore	Movable	-	Sank during emplacement -- never occupied

IKHTIANDR



1966 **1967** **1968**

Soviet Union, 1966–1968

The Ikhtiandr program, named after Ikhtiandr, or "fish man," the hero of a science-fiction novel by Soviet writer Alexander Belyayev, was one of the earlier Soviet habitat efforts. It was conducted by the Donetsk Social Laboratory of Underwater Research under the Scientific-Technical Society of Miners and Geologists and to study humans and equipment on the seafloor. The Ikhtiandr '66 habitat was a rectangular compartment with an arched roof and an air-locked hatch (Fig. 9-12*A*). It strongly resembled an underwater mailbox. The hatch extended 3.3 feet (1.0 m) below the wooden floor and had a ladder for entering. The habitat also contained four ports in the walls and ceiling. Power was supplied from shore, as was

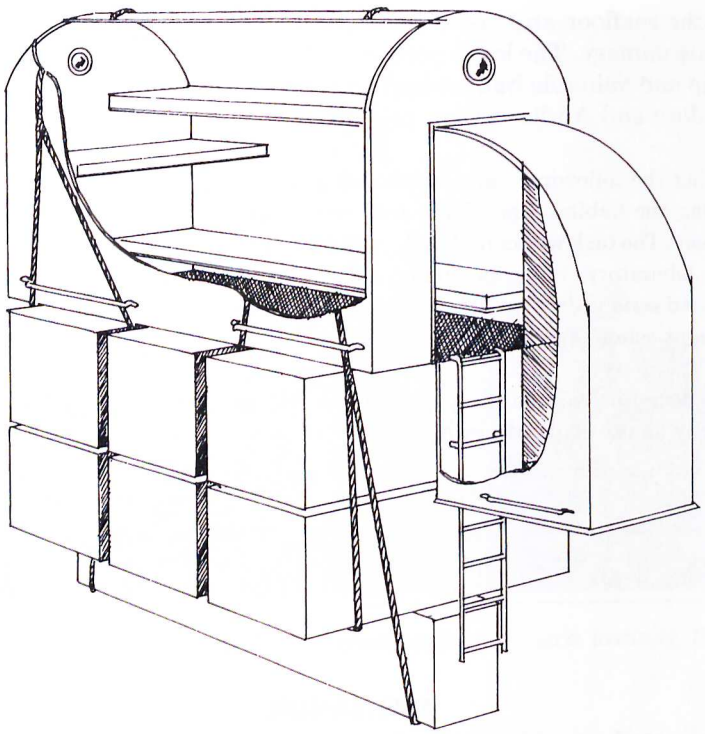


Figure 9-12. *A:* Ikhtiandr 1966. *(After J. Baras, S. Guljar, and J. Kiklewitsch, 1973, The Ikhtiandr Experiments, Poseidon 4(136):159.)*

the compressed air used for the breathing gas and communications. Food was provided from shore daily and was transported in thermos containers, rubber bags, and special boxes.

The site chosen for the first experiment was the Mys Tarkhankut region on the western Crimean coast. The habitat was located about 131 feet (40 m) offshore at a depth of 39.4 feet (12 m) and was anchored to the bottom with seven large concrete clumps weighing about 10 tons. The habitat was outfitted with food, medical recording instruments, emergency breathing gas, and miscellaneous supplies. The temperature inside the habitat during the mission ranged from 69.8° to 73.4°F (21° to 23°C), with an average humidity of about 90%.

The first of the three aquanauts, A. Khayes, a surgeon, entered the habitat on the morning of August 23, 1966. His first day was spent making excursions, catching fish for dinner, and visiting with divers dropping in from the surface. He was joined that night by a second

aquanaut. Khayes returned to the surface at the end of 3 days after breathing a helium-oxygen mixture for 2 hours and making 20-minute decompression stops at depths of 23 and 9.8 feet (7 and 3 m) (Sovetskaya Rossiya, 1966). Because of bad weather, the third aquanaut did not enter the habitat until the following morning. This is one of the few times when a single aquanaut was on the seafloor for an overnight stay. The program was terminated at the end of 7 days due to bad weather. The experiment was completed safely and without mishap.

For Ikhtiandr '67 a new and larger habitat was built. It was designed to house five aquanauts and offered comforts not included in the original (Trankvillitsky, 1967). It consisted of three metal cubes 23 × 28.2 feet (7.0 × 8.6 m) attached to a central entrance hatch (Fig. 9-12*B*). Over 100 persons, including scientists, engineers, physicians, and miners, were involved in the project.

The habitat was launched at Laspi Bay in the Black Sea off the south coast of the Crimea at a depth of 40 feet (12.2 m) in the summer of 1967. Two teams of aquanauts lived on the seafloor for 1 week each. The five aquanauts comprising the first team were all male. They were replaced at the end of a week by another all-male team. At the end of 4 days, two of the aquanauts on the second team surfaced and were replaced by two female aquanauts, Mariya Barats, a physician, and Galina Guseva, a graduate student, who remained on the seafloor for the final 3 days of the experiment (Guseva, 1967).

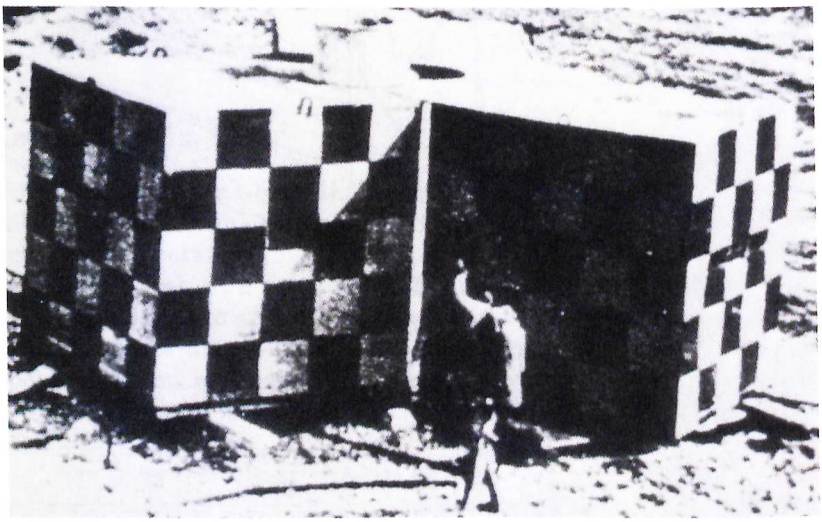


Figure 9-12. *B*: Anonymous Ikhtiandr 1967, *(Morze, 10, 18.)*

Marine geological experiments were carried out, and many measurements were made on the aquanauts. The program was carried out successfully, and plans were made immediately for future Ikhtiandr habitats.

A third habitat was built. Named Ikhtiandr '68, it was designed for four aquanauts and was used for a 3-day mission in August 1968, also in Laspi Bay (Fig. 9-12*C*) at a depth of 32.8 feet (10 m). The principal objectives of this mission were to obtain additional medical and physiological data on the four aquanauts. The breathing mixture was air.

The Ikhtiandr programs in 1969 and 1970 did not involve habitat

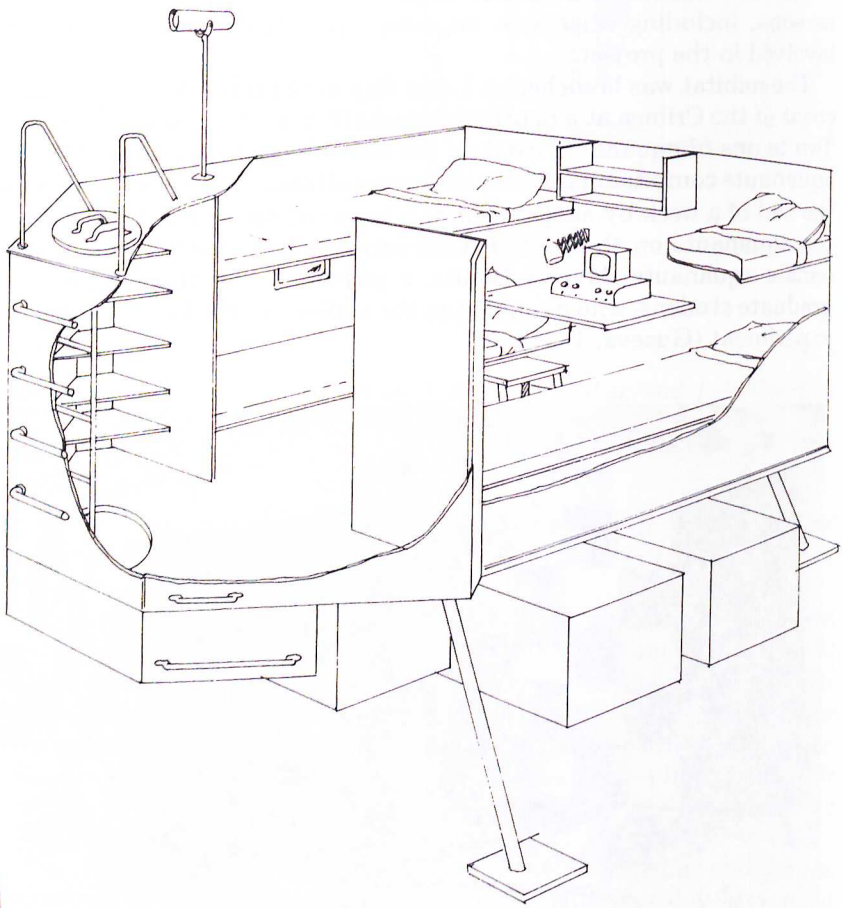


Figure 9-12. *C:* Ikhtiandr 1968. *(After J. Baras, S. Guljar, and J. Kiklewitsch, 1973, The Ikhtiandr Experiments, Poseidon 4(136):160.)*

operations. Rather, they were carried out in shore-based laboratories and included studies of elevated oxygen levels on future aquanauts and the development of diving suits. In 1969, divers spent periods of up to 8 hours sitting under water in these suits and were able to eat and drink while in the suits on the seafloor. In 1979 divers spent up to 37 hours in a rubberized suit with a fiberglass helmet on the seafloor at depths ranging from 16.4 to 32.8 feet (5 to 10 m) in water temperatures of 62.6° to 69.8°F (17° to 21°C) while medical and psychological data were collected (Baras, Guljar, and Kiklewitsch, 1973).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Ikhtiandr	USSR	1966	Crimean Coast Black Sea	12	3	7	L=2.2 W=1.6 H=2.0	10 Bal.	Air	Shore	Readily movable	-	-
Ikhtiandr	USSR	1967	Crimean Coast Black Sea	12.2	2-5	7	3 cubes L=8.6 H=7.0	-	Air	Shore	Readily movable	-	2 female aquanauts
Ikhtiandr	USSR	1968	Crimean Coast Black Sea	10	4	3	-	-	Air	Shore	Readily towable	-	-

KARNOLA



Czechoslovakia, 1968

Very little is known about this Soviet bloc habitat. It was reported in only one source, which in mid-1968 described it as the newest Czech underwater laboratory (Fig. 9-13). It was to house a female aquanaut for a period of 1 week at a depth of 26.2 feet (8 m). The next phase of the program called for a crew of five divers to spend 3 days at a depth of 49.2 feet (15 m). It also was reported that during one mission, the crew operated a ham radio station from the seafloor. Karnola was the third Czech habitat and followed the development of Permon I and II.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Karnola	Czech	1968	-	8 15	5	3-7	H=7.0	-	-	-	Readily movable	-	-

Marine geological experiments were carried out, and many measurements were made on the aquanauts. The program was carried out successfully, and plans were made immediately for future Ikhtiandr habitats.

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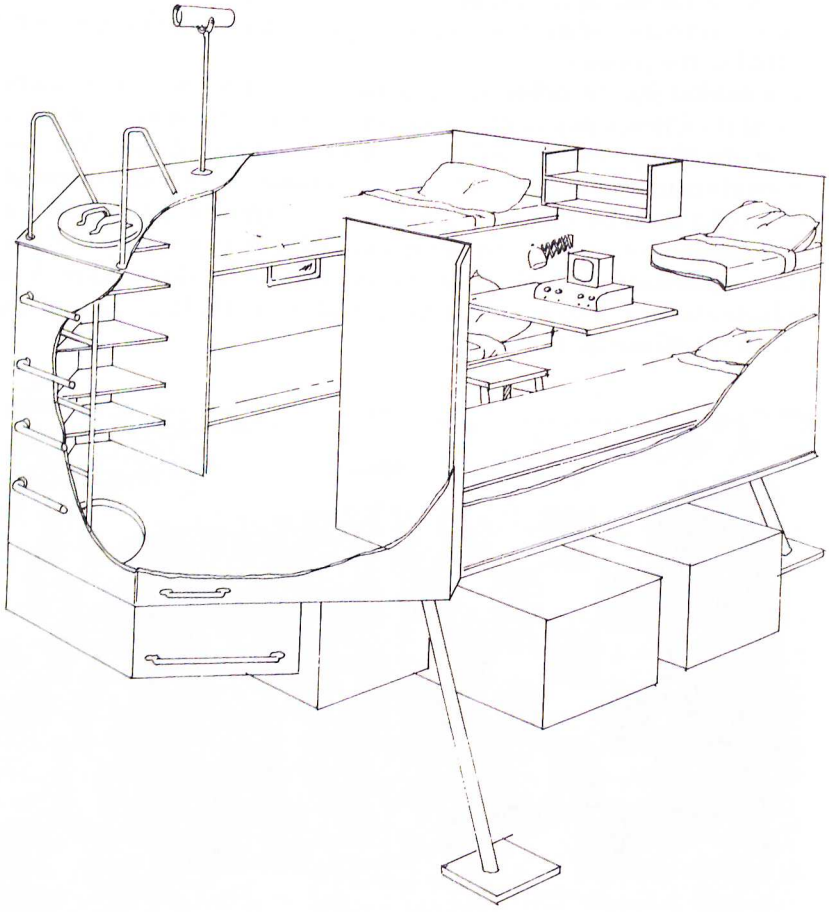

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Tekhlandr	USSR	1966	Crimean Coast Black Sea	12	3	7	L=2.2 W=1.6 H=2.0	10 Bal.	Air	Shore	Readily movable	-	-
Tekhlandr	USSR	1967	Crimean Coast Black Sea	12.2	2-5	7	3 cubes L=8.6 H=7.0	-	Air	Shore	Readily movable	-	2 female aquanauts
Tekhlandr	USSR	1968	Crimean Coast Black Sea	10	4	3	-	-	Air	Shore	Readily towable	-	-

KARNOLA



Czechoslovakia, 1968

Very little is known about this Soviet bloc habitat. It was reported in only one source, which in mid-1968 described it as the newest Czech underwater laboratory (Fig. 9-13). It was to house a female aquanaut for a period of 1 week at a depth of 26.2 feet (8 m). The next phase of the program called for a crew of five divers to spend 3 days at a depth of 49.2 feet (15 m). It also was reported that during one mission, the crew operated a ham radio station from the seafloor. Karnola was the third Czech habitat and followed the development of Permon I and II.

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Karnola	Czech	1968	-	8 15	5	3-7	H=7.0	-	-	-	Readily movable	-	-

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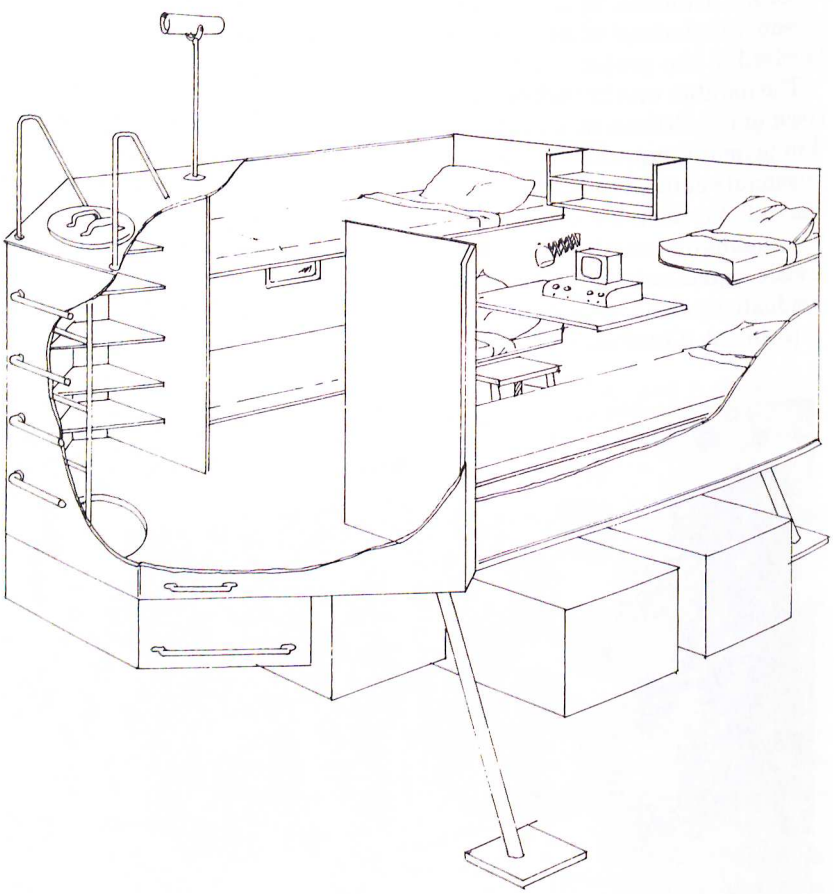

Figure 9-12. C: Ikhtiandr 1968. *(After J. Baras, S. Guljar, and J. Kiklewitsch, 1973, The Ikhtiandr Experiments, Poseidon* ***4****(136):160.)*

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logical data on the four aquanauts. The breathing mixture was

The Ikhtiandr programs in 1969 and 1970 did not involve

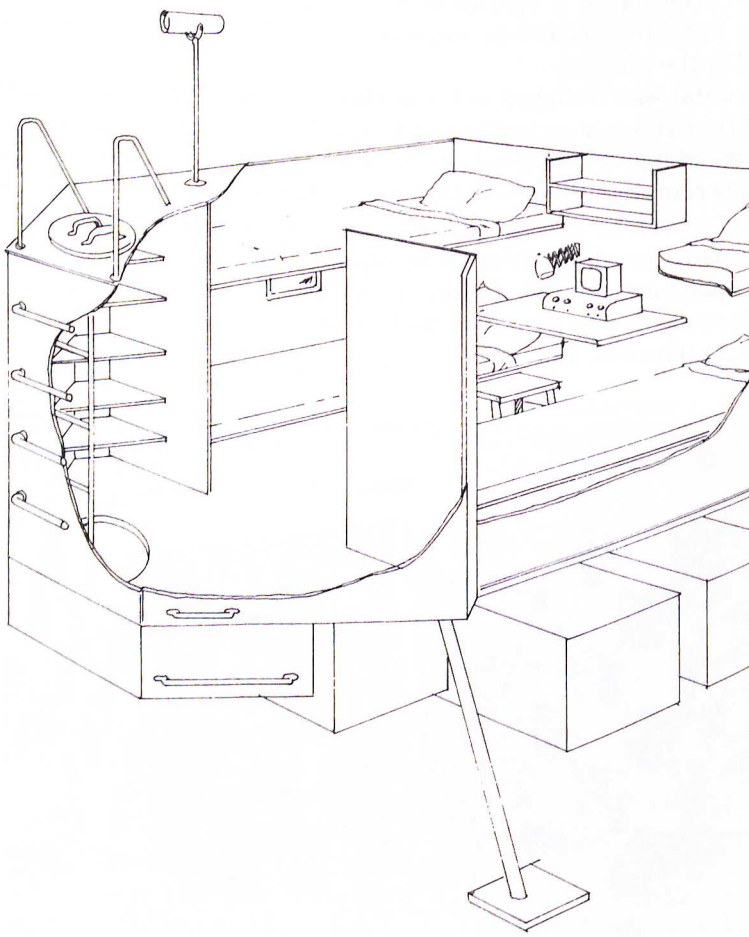
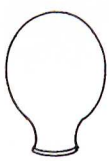


Figure 9-12. C: Ikhtiandr 1968. *(After J. Baras, S. Guljar, and J. Kik
1973, The Ikhtiandr Experiments, Poseidon* ***4****(136):160.)*

operations. Rather, they were carried out in shore-based laboratories and included studies of elevated oxygen levels on future aquanauts and the development of diving suits. In 1969, divers spent periods of up to 8 hours sitting under water in these suits and were able to eat and drink while in the suits on the seafloor. In 1979 divers spent up to 37 hours in a rubberized suit with a fiberglass helmet on the seafloor at depths ranging from 16.4 to 32.8 feet (5 to 10 m) in water temperatures of 62.6° to 69.8°F (17° to 21°C) while medical and psychological data were collected (Baras, Guljar, and Kiklewitsch, 1973).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Ikhtiandr	USSR	1966	Crimean Coast Black Sea	12	3	7	L=2.2 W=1.6 H=2.0	10 Bal.	Air	Shore	Readily movable	-	-
Ikhtiandr	USSR	1967	Crimean Coast Black Sea	12.2	2-5	7	3 cubes L=8.6 H=7.0	-	Air	Shore	Readily movable	-	2 female aquanauts
Ikhtiandr	USSR	1968	Crimean Coast Black Sea	10	4	3	-	-	Air	Shore	Readily towable	-	-

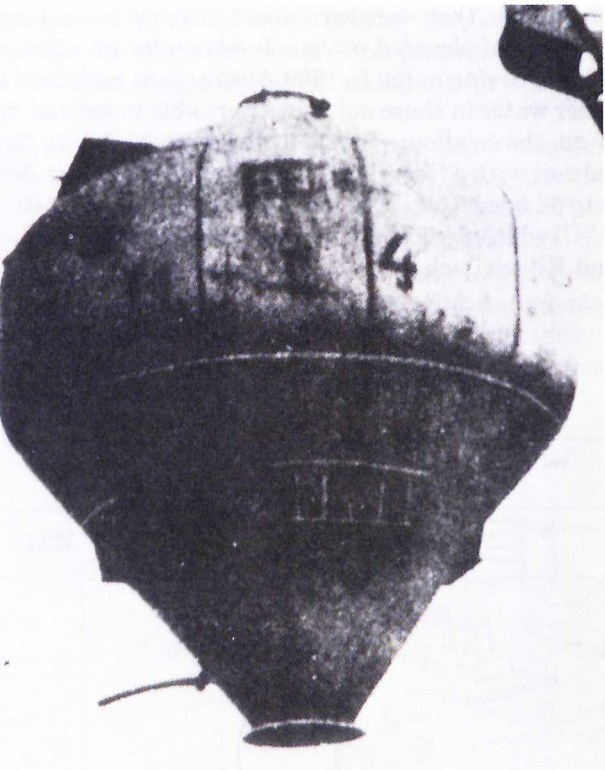
KARNOLA



Czechoslovakia, 1968

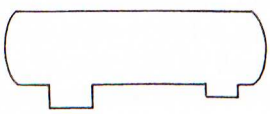
Very little is known about this Soviet bloc habitat. It was reported in only one source, which in mid-1968 described it as the newest Czech underwater laboratory (Fig. 9-13). It was to house a female aquanaut for a period of 1 week at a depth of 26.2 feet (8 m). The next phase of the program called for a crew of five divers to spend 3 days at a depth of 49.2 feet (15 m). It also was reported that during one mission, the crew operated a ham radio station from the seafloor. Karnola was the third Czech habitat and followed the development of Permon I and II.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Karnola	Czech	1968	-	8 15	5	3-7	H=7.0	-	-	-	Readily movable	-	-



. Karnola. *(From Anonymous, 1968, Karnola—New Czech Habitat, 78):277.)*

KITJESCH



nion, 1965

re in the market for an off-the-shelf habitat, no one could do ter than four divers from Moscow's Del'fin Underwater Sports ir plans called for converting an obsolete railway tank car to a abitat. Not only was their approach novel, but it also was the

subject of the first article indicating Soviet interest in a domestic habitat program (Anon., 1965, p. 10):

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> This habitat will be a 25-ton tank. Right now, it is being equipped to provide a sufficiently comfortable environment for a long stay under water. Eight view ports are being built into the sides and top. Initially, air, electricity, and freshwater will be fed from the Del'fin shore base. In the future, though, the habitat will become completely independent and also will be capable of being transported from place to place.

A survey of Soviet rolling stock revealed that only one suitable 25-ton tank car fit this description (Skiba, 1966). It was 20.6 feet (6.3 m) long and 7.2 feet (2.2 m) in diameter (Anon., 1965). According to Haux (1969), the tank was divided into three chambers. The two end chambers were living quarters, and the center compartment was equipped with control stations, sanitary facilities, and showers. Twelve ports were used for observation, and two entrances were cut in the tank.

Nothing more is known of Kitjesch, named for a sunken city in Russian mythology, not even whether it was used. It probably was not used because the Soviets characteristically gave a lot of publicity to such programs; if Kitjesch had been launched, it would have preceded the Caribe-I project sponsored by the Czechs and the Cubans in July 1966.

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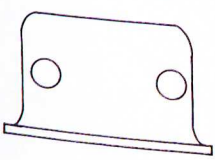
Kitjesch (Atlantis)	USSR	1965	Crimean Coast	15	4	-	L=6.3 W=2.2	25	-	Shore	-	-	Made from a converted Railroad tankcar

KLOBOUK



Czechoslovakia, 1965

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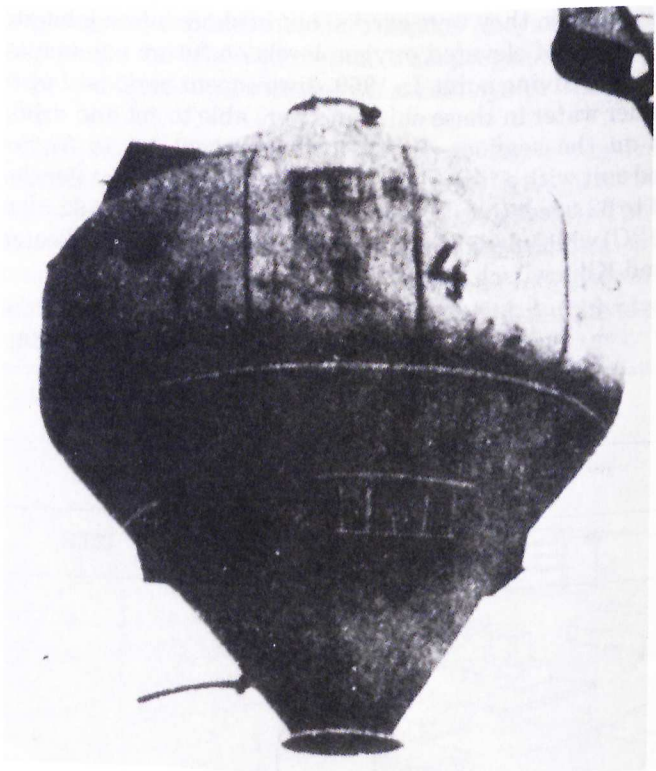
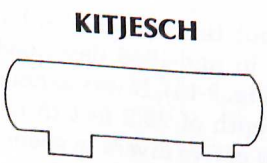


Figure 9-13. Karnola. *(From Anonymous, 1968, Karnola—New Czech Habitat, Poseidon 6(78):277.)*



Soviet Union, 1965

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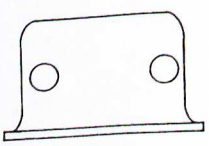

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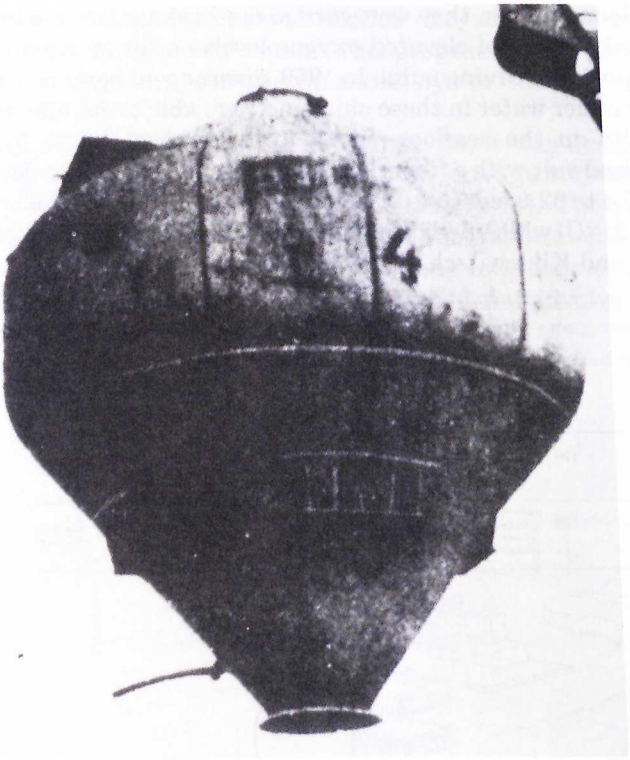
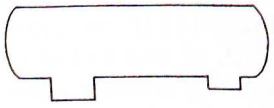


Figure 9-13. Karnola. *(From Anonymous, 1968, Karnola—New Czech Habitat, Poseidon* ***6****(78):277.)*

KITJESCH



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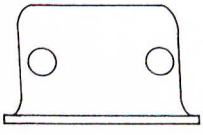


Czechoslovakia, 1965

Klobouk ("hat") was more of a way-station than a habitat. The body of the habitat was constructed from a discarded industrial cauldron, and

improvised components were used wherever possible (Fig. 9-14). For example, a common compressor was employed to deliver air through a tube to a plastic bucket, thus providing the aquanauts with an air supply. Four view ports were cut into the cauldron, and light and phone facilities were installed. The main body was secured to a bottom platform on which the aquanauts stood, which resulted in only the upper part of their bodies being dry in the "hat". The system was designed to accommodate up to four people and to house a table, stools, and a steel cylinder for an unknown purpose.

The first tests were conducted in a flooded quarry near Kozarovice, Czechoslovakia. Plans at the time called for further tests in the open sea. It is not known whether these tests were ever conducted (Fisera, 1968).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Klobouk (Hat)	Czech	1965	Kozarovice	6	4	Daily visits	L=1.2 H=1.0	-	Air	Shore	Readily movable	-	-

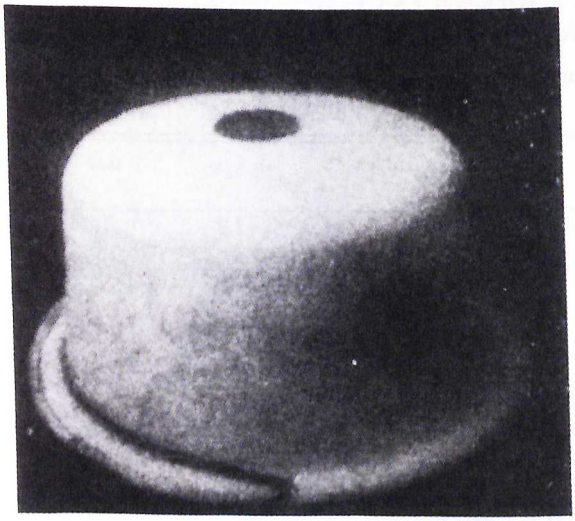
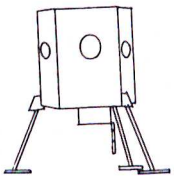


Figure 9-14. Klobouk. *(From H. Fisera, 1968, A Tent, a Hat, and a Microscaph, Poseidon* ***8****(80):366.)*

LAKELAB



United States, 1972

Lakelab was developed by the University of Michigan as a simple low-cost facility for the support of educational and research activities. Although it was designed to support two persons at depths not exceeding 50 feet (15.2 m) for periods up to 48 hours, the longest time spent inside was 4 to 5 hours. Life support was supplied from either shore or a surface craft, although Lakelab did contain an autonomous lighting system. The habitat was capable of being towed for short distances and had three adjustable legs to permit it to be emplaced on an uneven bottom (Fig. 9-15). The entry trunk was approximately 2×5 feet (0.6×1.5 m) and was equipped with a hatch and a ladder. One 30-inch (76.2 cm) and two 16-inch (40.6 cm) ports were provided.

The habitat was transported by a flat-bed truck, lifted into the water by a crane, and winched to the bottom. The shore-control center was located in a mobile van equipped with communications equipment, compressors, emergency equipment, and other equipment.

Lakelab operations were located in Lake Michigan's Grand Traverse Bay close to shore near the Omena-Traverse Yacht Club. Although designed to operate at depths to 50 feet (15.2 m), operations were limited to a depth of 26 feet (7.9 m) so as to eliminate the need for decompression following a mission. A depth of 26 feet (7.9 m) appears to be the maximum depth from which one can return to the surface without decompressing.

After 2 or 3 years of disuse, the habitat was reduced to scrap in the fall 1975. Prior to that, it had been used for environmental studies, engineering evaluation, and saturation diving training (Somers, 1973). As a training station, it was quite successful; over 200 students had the opportunity to spend several hours on the lake bottom.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Lakelab	U.S.A.	1972	Grand Traverse Bay, Michigan	15.2	2	2	D=3.0 H=2.1	24 Bal.	Air	Shore	Readily movable	N/A	-

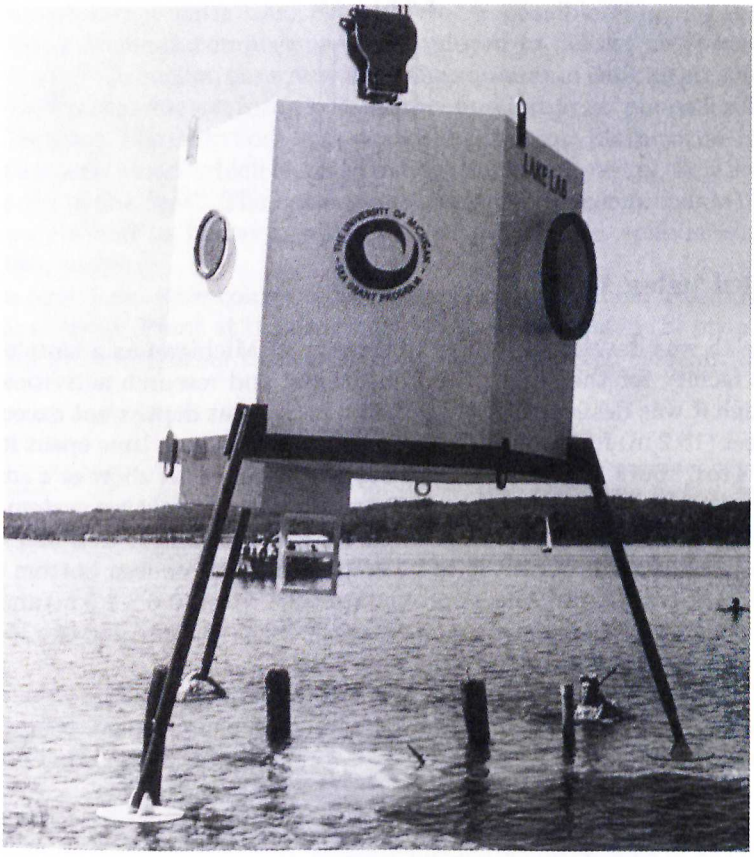
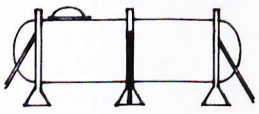


Figure 9-15. Lakelab. *(Copyright © 1972 by the Great Lakes Foundation; courtesy of Great Lakes Foundation, Ann Arbor, Michigan.)*

LORA



Canada, 1973–1975

In early 1973, the LORA habitat was developed by members of the Memorial University of Newfoundland located in St. John. The 8 × 16 foot (2.4 × 4.9 m) habitat was designed to be used in shallow water at depths less than about 30 feet (9.1 m) (Fig. 9-16). LORA's first mission was on

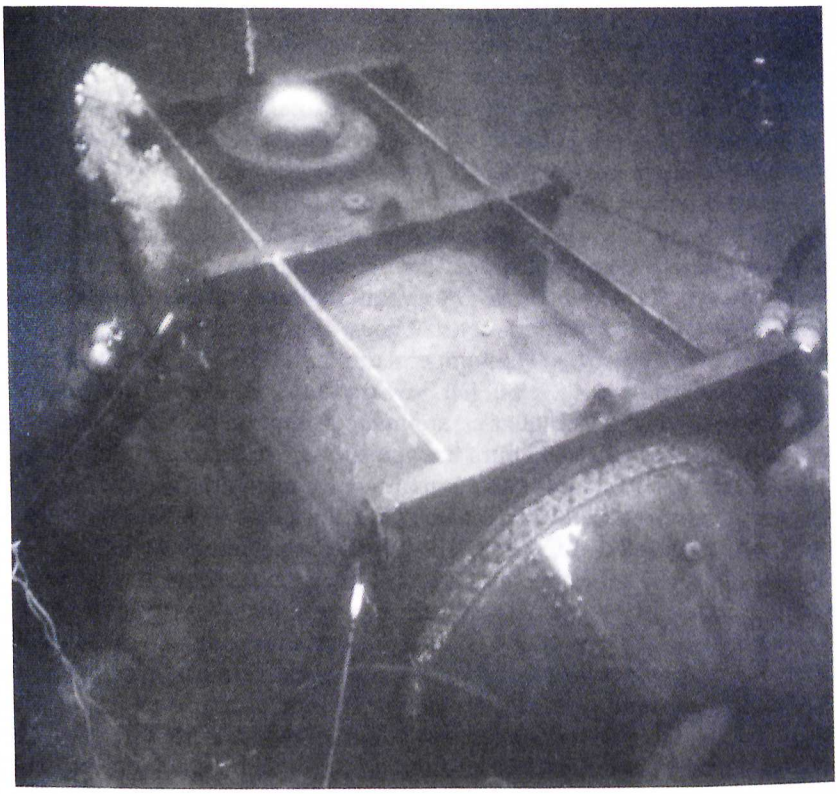
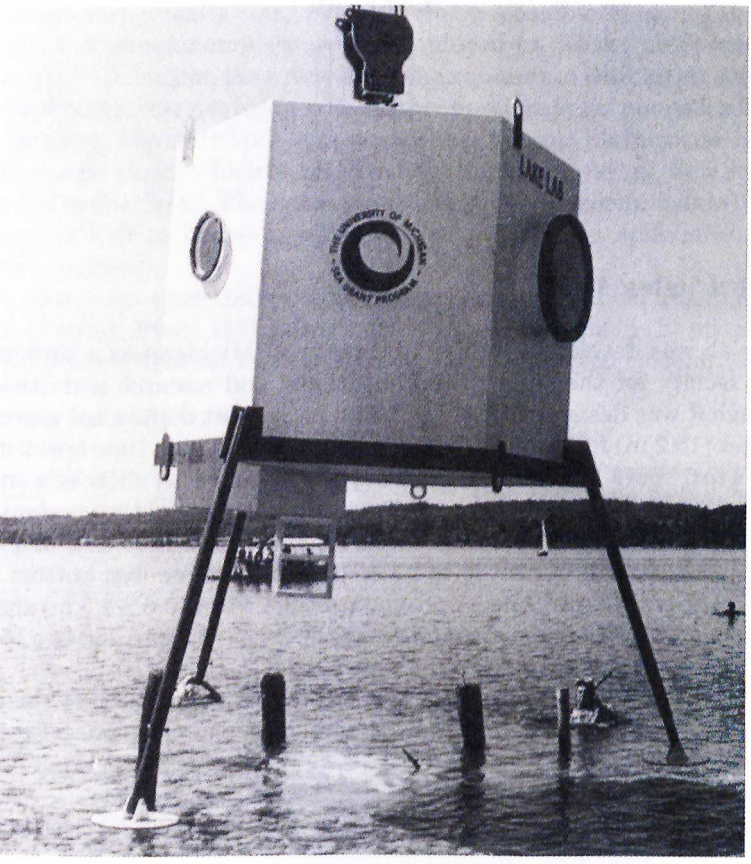


Figure 9-16. LORA. *(Courtesy of J. Morgan Wells, National Oceanic and Atmospheric Administration, Rockville, Md.)*

August 22-23, 1973, in the cold waters off St. Phillips at a depth of 26 feet (7.9 m). Air was used both for the habitat breathing gas and for diving. During this 24-hour mission, the two aquanauts evaluated the habitat, conducted routine hull maintenance, observed fish behavior, and tested a new decompression procedure. While on the seafloor, the aquanauts made four excursions to a depth of 35 feet (10.7 m), of which three were for 60 minutes and one for 75 minutes. No difficulties were encountered during any of the excursions.

On completion of the fourth excursion, the two aquanauts spent 8 hours in the habitat at the storage depth of 26 feet (7.9 m), after which they proceeded directly to the surface with no decompression stops. No symptoms of bends were noted by either diver. The investigators concluded that "the divers did not reach full saturation at the hatch depth" but that the "length of the dive was such that this was approached"



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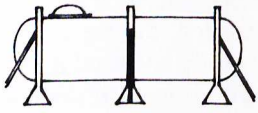

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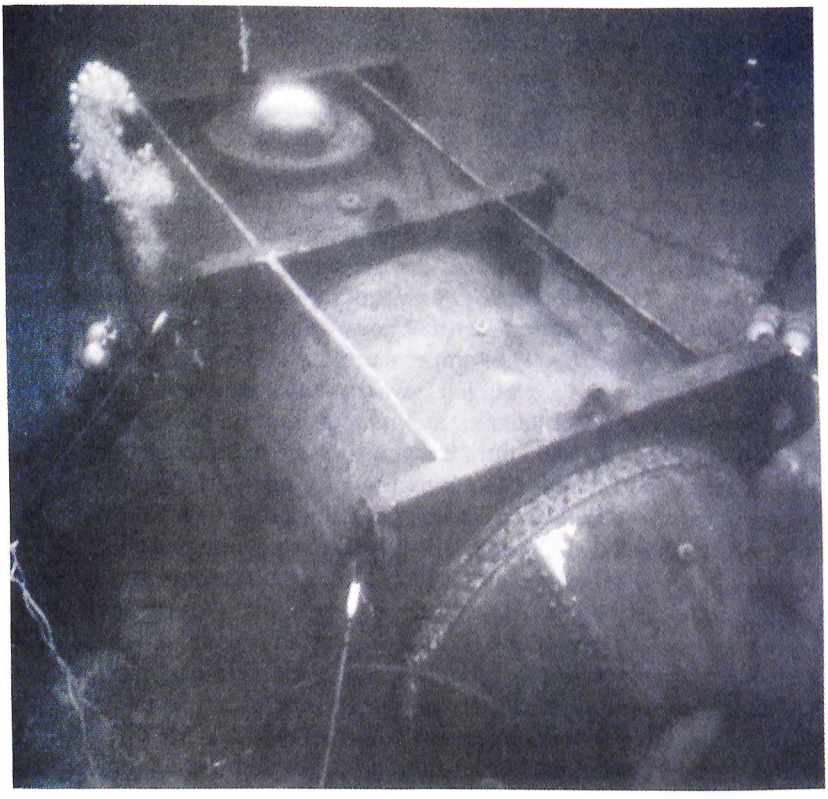

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(English, 1973, p. 23). The 8-hour soak period at the 26-foot (7.9 m) storage depth following the fourth excursion was required to allow the nitrogen taken up during the excursions to be released and the tissues to reach equilibrium with that depth. The investigators further concluded, "It is possible to surface directly when fully saturated at the hatch depth of 26 feet" (English, 1973, p. 23).

During April 6-7, 1974, LORA was used for a simulation saturation mission in preparation for an arctic dive to take place in May using the SPID habitat (Fig. 3-9). The LORA program again took place in the frigid waters off Newfoundland. The aquanauts were saturated at a depth of 35.2 feet (10.7 m) on air for about 29 hours. Water temperatures were a chilling 28.6°F (−1.9°C). The temperature inside the habitat was only slightly more being 46.4°F (8.0°C). Previous experience in subzero water temperatures indicated that over a single 24-hour period, divers could expect to complete up to 8 hours bottom time in relative comfort.

The primary work task was to prepare a photogrammetric map of the area surrounding the habitat. Twelve excursion dives were made by each aquanaut, for a total of 5.2 hours in the water per man. To assess the thermal effects of the cold water on the divers, body core temperature was monitored. Although the final three excursions were shortened due to fatigue and cold, the core temperature varied within normal limits. Accordingly it was concluded that "an intensive excursion profile could be applied successfully to the arctic with minor alterations" (English, 1974*a*, p. 13). The dive parameters are summarized in Table 9-1. On completing the 28.8-hour mission, the aquanauts decompressed for approximately 12 hours.

Table 9-1. Summary of 1974 LORA Simulation Dive

Dive Parameters	*Proposed*	*Actual*
Overall task accomplishment	60-90%	80%
Water temperature (°C)	-1.0	-1.9
Interior temperature (°C)	7.0±2	8.0
Core temperature variation (°C)	1.5	2.0
Depth (m)	10.8	10.8
Total duration (hr)	34.75	28.76
Number of excursions (per man)	12	12
Total excursion duration (hr)	9.5	5.2
Mean excursion time (min/man)	47.5	26.0
Mean rest period (min)	126.25	117.8
Excursion duration/dive duration	27.4%	18.1%

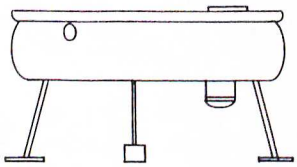
Source: From J. English, 1975, Shallow Air Saturation Dive in the High Arctic, in *Ocean '75*, IEEE Publication 75 CHO 996, San Diego, Calif., Dec. 1, p. 265. Copyright © 1975 by the Institute of Electrical and Electronics Engineers, Inc.

Between February 12 and 15, 1975 a third mission using LORA was carried out at a depth of 26 feet (7.9 m), the same depth as the 1973 mission. On this occasion, the habitat was placed under the ice, with the water temperature being 28.6°F (−1.9°C), a drastic reduction compared with the relatively warm water of 54.5°F (12.5°C) during the 1973 summer mission and more in keeping with the 1974 simulation dive.

Thirty-six man-excursions to a depth of 35 feet (10.7 m) were made by the three aquanauts. The average excursion time was 38 minutes, with the longest being 54 minutes. After completing the mission, the aquanauts breathed oxygen for six 20-minute periods, with 5-minute periods in between breathing habitat air. This procedure was designed to allow the three aquanauts to surface as quickly as possible after the last excursion. Following this procedure, the aquanauts entered the water and swam directly to the surface. Eighteen hours later they flew from Newfoundland to Montreal. No symptoms of decompression sickness were noted. The most interesting aspect of this program is documentation of the fact that direct ascent to the surface can be made safely from a saturation dive at a depth of 26 feet (7.9 m). The LORA habitat has not been used for any more missions.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
LORA	Canada	1973–1975	Newfound-land	7.9	2	1	L=2.4 D=4.9	24 Bal.	Air	Shore	Fixed	0	Under ice

LS-I
(LABORATORUL SUBMERS-I)



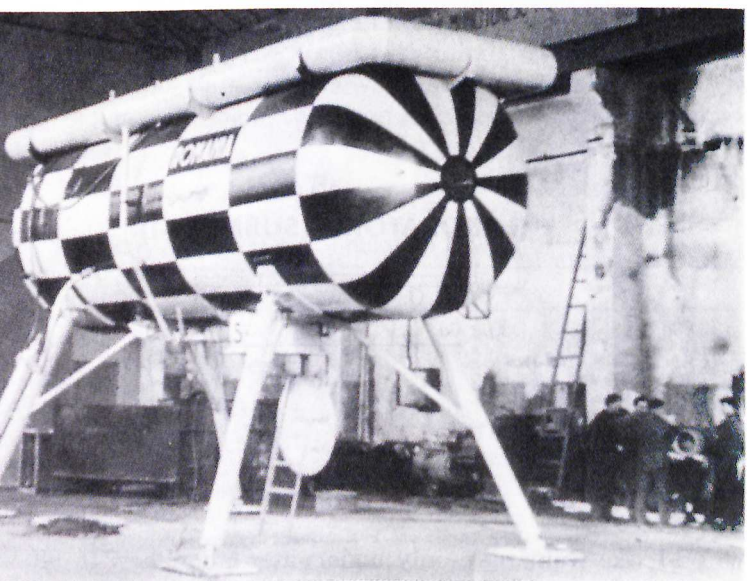
Rumania, 1967

The LS-I was Rumania's only underwater laboratory. It culminated a series of underwater surveys made on the Rumanian shores of the Black Sea that began in 1962. The objective of the LS-I program was to conduct an initial underwater project in an inland lake, to be followed by a program in the Black Sea. The habitat was designed and built by engi

G. Morariu and C. N. Ignatescu in the winter of 1966 at one of kshops of the Regional Enterprise for Electric Power from Bicaz 1970).

abitat, which took only 5 months to build, was a 7.9 × 24.3 foot 4 m) steel cylinder with a volume of 1165 feet^3 (33 m^3) and a dry of 13 tons. The initial design called for a smaller habitat weighing . During the design phase, however, a 43-foot (13 m) pressure as located and obtained free from a nearby chemical plant. This cal chamber was modified and hemispherical ends added to form I. Subsequently it was tested for 24 hours at an internal pressure si, and the 0.79 inch (20 mm) walls were found to perform well u, pers. commun.).

ned to house five aquanauts for up to 30 days, the LS-I had four (25 cm) ports and four supporting legs (Fig. 9-17). The LS-I was into two compartments, the hold, which contained the 20 tons of and the living quarters, which held two desks and two bunks. ent in the habitat included the atmospheric control system, , and communications, including closed-circuit television. Air d as the breathing gas. Although all life-support requirements



17. LS-I. *(From I. G. Morariu and Ignatescu, 1972, Le laboratorie submerge app. Comm. Int. Medit.* ***20****(4):767.)*

were supplied from the surface, there were emergency backup systems on board.

The LS-I was launched on September 29, 1967, in Lake Bicaz, a man-made mountain lake that formed the Izvorul Muntelui Reservoir on the Bistrita River. At this time, the habitat was loaded with 20 tons o iron ballast, and all systems were tested. Weather, equipment, and admin istrative problems prevented a manned mission from being achieved a this time, and operations were terminated in late October. Additiona administrative and organizational problems precluded manned opera tions during 1968 and 1969.

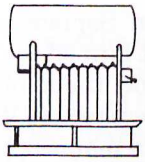
The first unmanned underwater test was carried out in 1969 at a dept of 39 to 45 feet (11.9 to 13.7 m). In 1970, a 30-day manned mission wa achieved by the Stejarul Experimental Station of Pingarati in coopera tion with the A. I. Cuza University of Jassy (Anon., 1973). The actua saturation depth was about 33 feet (10 m) because the legs were designe to keep the hatch 8.3 feet (2.5 m) above the bottom. Water temperatures i Lake Bicaz varied from 36°F (2°C) in the winter to 77°F (25°C) at th end of summer. The habitat's electrical heating system kept the insid temperature within the comfortable range of 80° to 84°F (27° to 29°C

During the mission, the three aquanauts observed behavior of aquat organisms, the biorhythm of fish, and gathered data on other life in th lake. Excursions were made to distances up to 82 feet (25 m) from th habitat. Decompression was accomplished by slowly raising the habit to the surface during the final 48 hours of the mission. This techniqu also was used earlier by the Polish in the 1967-1968 Meduza program an later by the Israelis in the 1977 Neritica program. Although the LS program originally called for the use of oxygen during decompression, was not used because of the added cost.

The LS-I has been used for one 30-day mission per year since 197 usually at depths of about 39 feet (11.9 m) for teams of two to fo aquanauts. Although developed originally for use in the Black Sea, th LS-I has been used exclusively in Lake Bicaz, with the last know saturation mission taking place in 1980. As recently as August 198 however, it still was being used as an observation station in Lake Bicaz f studying fish behavior (Morariu, pers. commun.).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARK
LS-I	Rumania	1967-1981	Lake Bicaz	12-14	3-4	30	L=7.2 D=2.4	20 Bal.	Air	Ship	Readily movable	48	Still used observatio

MALTER-I

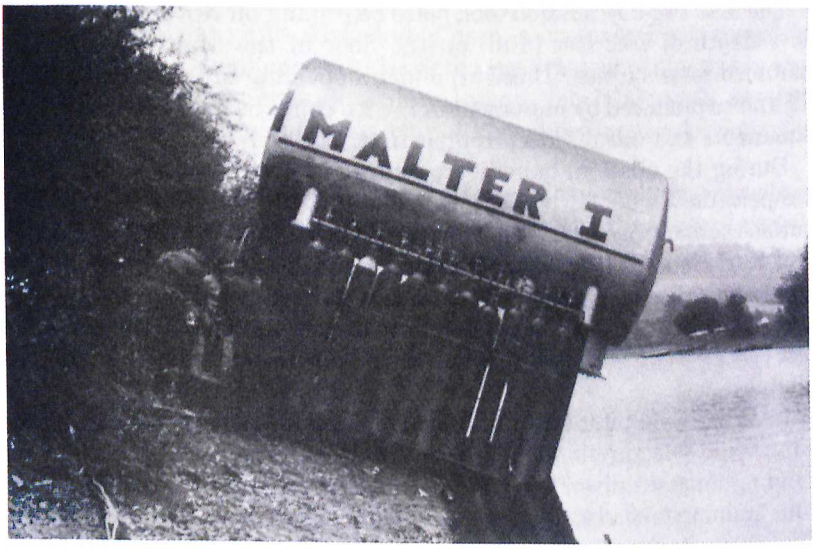


German Democratic Republic, 1968–

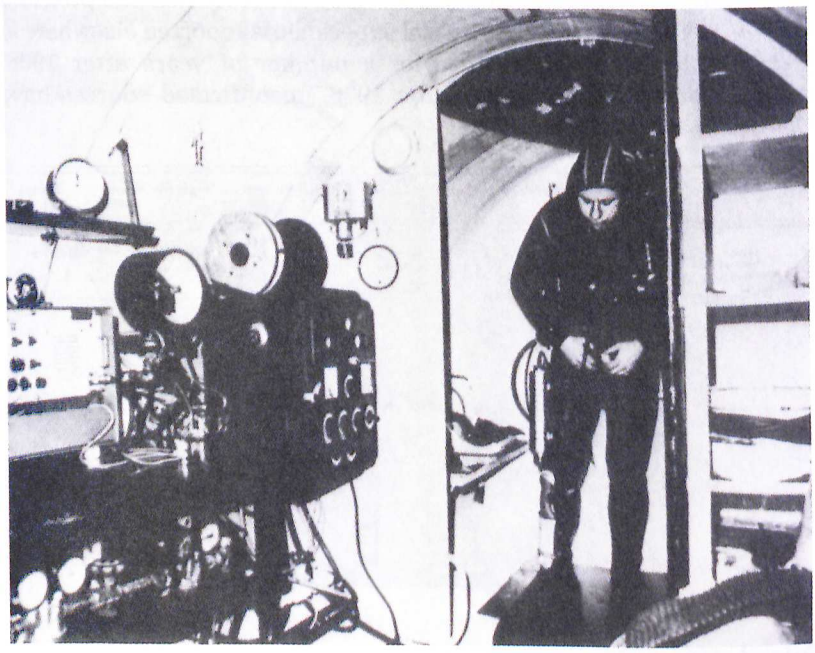
Malter-I, named for Malter Dam, the site of first mission, the first underwater habitat built in the German Democratic Republic, was conceived in November 1967 and launched one year later. It was designed by engineers Peter Fuchs and Manfred Boerner of the VEB Ferdinand Kunert Schmeideberg Branch Foundary Plant with the support of the Society for Sport and Technology of Paulsdorf (Erler, 1968). These sport divers were encouraged to undertake the project after learning of such programs as Link's Man-in-the-Sea, Cousteau's Conshelf series, the U.S. Navy Sealab-I, and the Soviet Sadko-I program (Kucher, 1973).

This readily transportable habitat was designed to house two aquanauts for periods of more than 1 week and four aquanauts for shorter times. Malter-I could be split into three sections for transportation: the air-filled cylinder, which housed the control equipment; the supporting structure containing ballast, gas cylinders, and other equipment; and a second support structure that served as a base and additional ballast (Fig. 9-18). The overall length of the habitat was 13.8 feet (4.2 m), with a diameter of 6.6 feet (2 m) and a gross weight of 14 tons, including ballast and gas cylinders.

The dry area of the habitat was divided into two sections, the wet room containing the entrance and the main living compartment, which had a 19-inch (48.3 cm) port (Fig. 9-18*b*) (Anon., 1968*b*). The main compartment was insulated and outfitted with a telephone, radio, and TV communications, plus the normal habitat amenities. Power was supplied either from shore or from batteries stored on the habitat (Anon., 1968*b*). The breathing gas was supplied from shore and was delivered to the habitat at ambient pressure through either an open or a closed-circuit system. Any combination of a nitrogen-oxygen mixture could be provided. The system also could supply pure oxygen. Malter-I was equipped with a CO_2 removal system and was insulated and heated so that the inside temperature could be maintained at 66.2°F (19°C) when the outside water temperature was as low as 37.4°F (3°C). Although designed for operations up to depths of 114.8 feet (35 m), as of 1973 the habitat never was used deeper than 32.8 feet (10 m) because of the lack of decompression facilities (Kucher, 1973).



A



B

Figure 9-18. Malter-I.*A*: Exterior view; *B*: interior view. *(Courtesy of Urania-Verlag, Leipzig, German Democratic Republic.)*

The first two-day mission took place beginning on November 13, 1968, at a depth of 26.2 feet (8 m) on the floor of the Malter-Talsperre (a dammed reservoir near Dresden) under a covering of ice (Anon., 1969). The noise produced by movement of the ice could be heard readily by the aquanauts and was disconcerting at first.

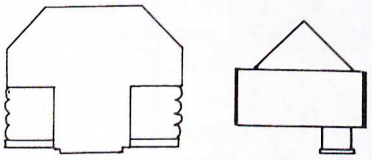
During the mission, humidity was kept at 65 to 70% and the inside temperature at 66.2°F (19°C) as planned. All food was provided by surface-support personnel. The first two aquanauts were Manfred Boerner and Karl-Heinz Foltyn whose primary activities on the bottom were to serve as medical subjects and to evaluate equipment. They made excursion dives to the bottom just 6.6 feet (2 m) below and up to the ice cover 26 feet (7.9 m) overhead. Because of poor visibility, a safety line was used on all dives.

In 1972, the habitat was overhauled and modifications made in the air supply and safety systems. After that, Malter-I served solely as a base for training amateur divers in working and scientific skills (Kucher, 1973). This training is carried out in 4-, 8-, or 24-hour sessions at depths that do not require decompression although decompression tables for saturation to depths up to (25 m) were worked out in 1972-1973.

The Malter-I program represents the first under-ice habitat program and is in sharp contrast to the tropical experiments reported elsewhere in this book. The habitat was used for a number of years after 1968. Although details are not known after 1973, unconfirmed sources have reported its use as late as 1983.

	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
er-I	German Democratic Republic	1968	Malter Dam	8	2-4	2-7	L=4.2 D=2.0	14	Air	Shore	Readily movable	-	Under ice

MEDUZA-I and MEDUZA-II

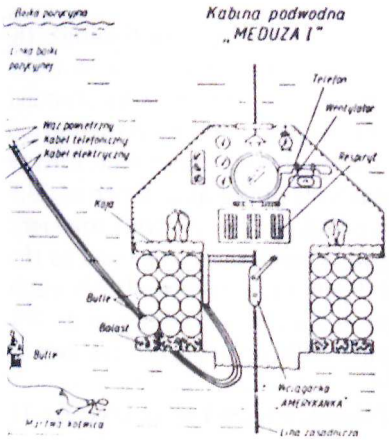


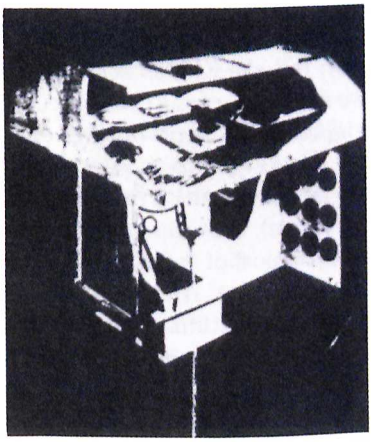
Poland, 1967-1971

Meduza-I (a meduza is a jellyfish), the first Polish habitat, was constructed in 1967 at the Komuna Paryska shipyard in Gdynia as a base for underwa-

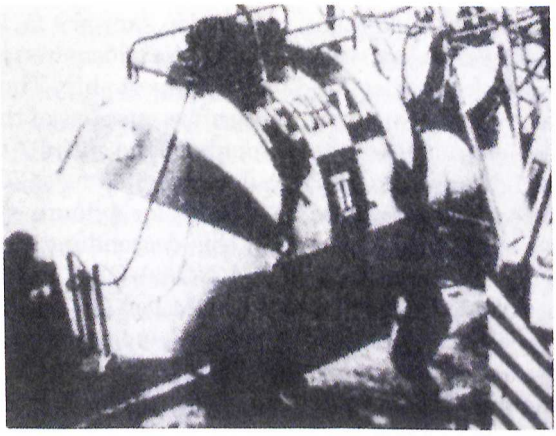
ter repairs and inspection. The design was proposed by Antoni Debski, a shipyard technician, and Aleksandr Lasso, a chemist (Podrazhanskiy, Rostarchuk, and Stephenov, 1973). Both were amateur scuba divers and were members of the Poseidon Skin-Diving Club in Gdansk, another example of the close link between sport diving clubs and the development of European habitats.

The habitat was comprised of two bolted sections, one above the other (Fig. 9-19a). The living compartment (upper section), the shape of a small





A



B

Figure 9-19. Meduza-I. A. *(From M. Sekhovich, 1968, Meduza-I Underwater Laboratory, Sudostroyeniye, no. 9, p. 18.) (From A. Debski, 1967, Ninety-five Hours Underwater, Morze* ***10:***4.). B. *(From H. Pajak, N.D., Z Czyms do Morza, Po Naszych Publikacjach, No. 48 [810], p. 20).*

ıouse, was 7.2 × 5.9 × 2.6 feet (2.2 × 1.8 × 0.8 m). The lower section, which ɔerved as the entrance trunk, was 2.0 × 2.0 × 3.3 feet (0.6 × 0.6 × 1.0 m) Debski, 1967). The habitat was well insulated with Styrofoam panels ɔecause the water temperature was to be only 44.6°F (7°C). The living ɔompartment contained gas monitoring equipment, heaters, and the ıecessary life-support facilities for two aquanauts. A port was located in ɛach end. An interesting feature of Meduza-I was its capability to ascend and descend using a hand winch system that could be operated from inside the habitat. This arrangement permitted the aquanauts to decompress inside the habitat by slowly raising it to the surface.

The first mission using Meduza-I took place from July 14 through 18, 1967, in Lake Klodno near the city of Kartuzy. The aquanauts were the two designers plus a colleague, Jerzy Kulinski. The mission was planned originally for 7 days but was shortened due to problems with insulation and some equipment. A problem also developed with the winch during emplacement, which resulted in the habitat's stopping at a depth of 78.7 feet (24 m). This was to be the saturation depth for the 95-hour mission. As with most of the other European programs, soda lime was used as the CO_2 absorbent. All power lines and umbilicals passed directly through the entrance trunk. The breathing mixture was 37% oxygen and 63% nitrogen. Decompression was accomplished with a very gradual ascent over a period of 53 hours and 35 minutes.

In 1968, a second habitat was built in Poland, referred to as Meduza-II (Fig. 9-19b). This habitat was larger and again was equipped with a self-lowering and -raising capability (Murawska, 1968). Also included were electric heating and lighting, two bunks, sanitary facilities, and a life-support system capable of sustaining the three aquanauts independently for 50 hours with air being supplied from a support ship. The scrubber or venting system must have been very efficient because one of the aquanauts smoked in the living compartment throughout the entire 7-day mission.

This initial 7-day mission was at a depth of 85.3 feet (26 m), during which the three-man crew worked on a wreck for 4 hours each day at a depth of 164 feet (50 m). Interestingly, this descending excursion time corresponds exactly with the modified NOAA-OPS excursion times described in Chapter 8 and contained in Miller (1979). The Meduza project was sponsored by the Enterprise for Dredging and Underwater Works and is one of the earliest working missions using a seafloor habitat. Decompression time at the end of the mission was 22 hours, less than half the time required for Meduza-I where the saturation depth actually was 6.6 feet (2 m) deeper. The Meduza-II habitat presumably was used for other working projects over the next five years.

In November 1971 Meduza-II was submerged during a demonstration

dive for representatives of the Polish Academy of Sciences and several industrial firms for the purpose of determining its use in future projects (Kubiak, 1972). It is not known whether additional programs actually were undertaken.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Meduza-I	Poland	1967	Lake Klodno	24	2	4	L=2.2 W=1.8 H=2.1	3.0	37% O_2 63% N_2	Shore	Readily movable	53.5	Entire habitat raised for decompression
Meduza-II	Poland	1968–1971	Gdansk, Baltic Sea	26	3	7	L=3.6 W=2.2 H=1.8	8	Air	Ship	Readily movable	22	Excursions to 50 m

NERITICA



Israel, 1977–

Neritica (named after the neritic region, the shallow water marine environment) is one of the most recently constructed habitats in the world. It was designed and fabricated from August 1977 to February 1978 at the Galmarin Ship Repairers in Eilat, Israel, under the direction of Gerd Helmers, Galmarin's director and marine engineer.

Financed solely by private funds, Neritica clearly reflects an interna tional cooperative effort, with technical and scientific assistance provide by experts from West Germany, Switzerland, England, and France. Th objective of the program was to construct a low-cost seafloor habita requiring minimal operating expenses to permit long-term scientifi studies of the Red Sea coral reefs on the Sinai coast of the Gulf of Eilat. I also was to mark the first step in the development of a man-in-the-se program in Israel (Fricke, 1977).

The habitat, shown in Figure 9-20*A*, was designed to accommodate u to three aquanauts in water depths of 36 feet (11 m). Due to the rais entrance, the pressure in the habitat was equivalent to about 26 to 29 fe (7.9 to 8.8 m) of seawater. Neritica, which was constructed of 0.10-inch

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Meduza-II	Poland	1968–1971	Gdansk, Baltic Sea	26	3	7	L=3.6 W=2.2 H=1.8	8	Air	Ship	Readily movable	22	Excursions to 50

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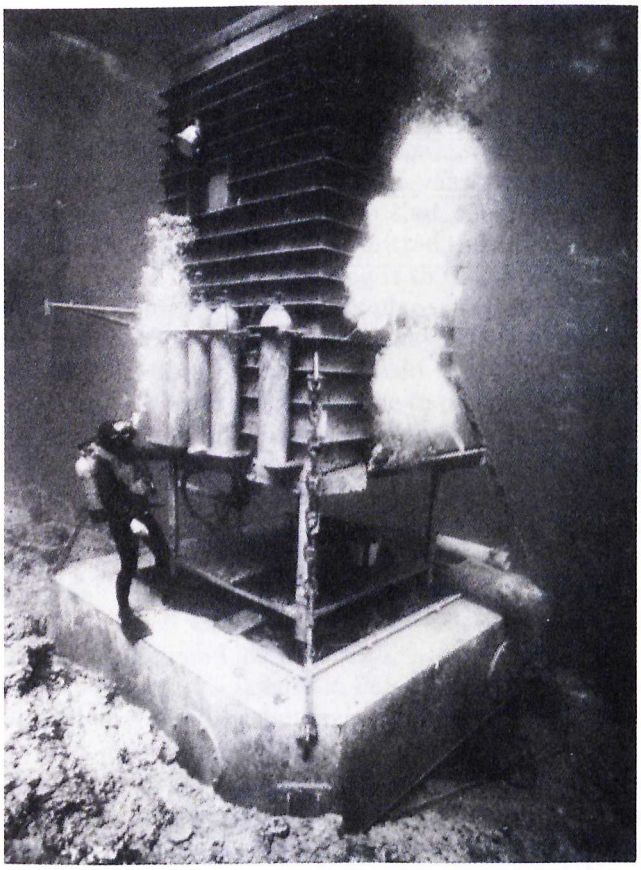


20. Neritica. *A:* Emplaced and operating on the seafloor (*courtesy of ke, Max-Planck-Institute fur Verhaltenphysiologie, Seewiesen, Federal of Germany.*

el, had overall dimensions of 6.5 × 11 feet (2 × 3.4 m) and was nto two compartments. One compartment served as a living and ry room, and the other was the wet room containing the 2 × 2 foot cm) entrance hatch (Fig. 9-20*B*). The dry weight of the habitat was 3 tons, with a total volume of 494 ft^3 (14 m^3). The primary 11 tons) was placed in a container under the entrance platform econdary ballast container holding an additional 12 tons of scrap e secondary container was fitted with chains and could be lifted d transported when the diving site was changed. Once in position, ooded and the habitat attached firmly, as shown in Figure 9-20*A*.

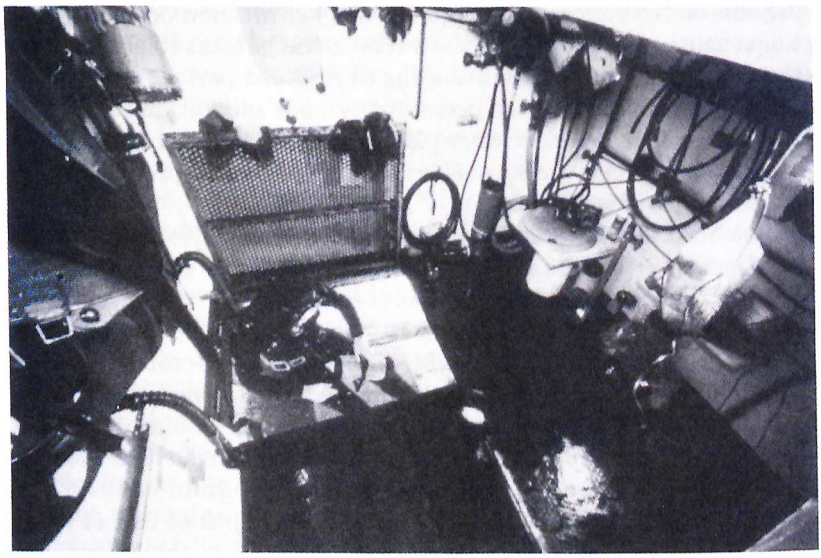


Figure 9-20. Neritica. *B*: Wet room showing entrance hatch. *(Courtesy of Hans Fricke, Max-Planck-Institut fur Verhaltenphysiologie, Seewiesen, Federal Republic of Germany.)*

The habitat itself was towed on the surface. An interesting feature of Neritica was the air-filled igloo suspended above the primary habitat. This enclosure apparently served two purposes: to control the ascent and descent of the habitat and to serve as a refuge and communication center once the habitat was emplaced on the the seafloor.

Neritica, which was not designed as a pressure vessel, contained four glass windows. It was equipped with a toilet, a hot water shower, two bunks, table, chairs, and other items. The wet room was designed so it could be flooded to increase the stability of the habitat in the event of bad weather. Neritica was supplied from shore with low-pressure air, electrical power, water, communications, and a closed-circuit TV system. Emergency power and supplies to sustain the habitat for 24 hours were located on board, along with exterior floodlights mounted on the top and at the entrance. A decompression chamber was located nearby on shore.

The habitat was activated in 1978. Early missions were concerned with coral reef ecology and the development of an ecosystem model. Fish behavior was studied around the clock. These studies involved placement of a large cage covered with a thin nylon net near the habitat for extended studies of captured reef fishes. Between 1978 and 1981, over 80 people worked in or visited Neritica on the seafloor, accumulating over 400

n-hours on the bottom. Although the longest mission occurred when aquanauts spent 16 days on the seafloor, the habitat itself remained he water for a continuous 12 months during one period.

Although Neritica was used occasionally as a saturation facility, its nary use was as an underwater platform, workshop, laboratory, and studio for special projects. Five feature television programs were ed on the Neritica program.

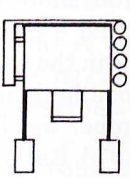
n June 1978, aquanauts in Neritica spoke for 25 minutes to aquanauts he German Helgoland Underwater Laboratory on the floor of the tic Sea. The only other time a habitat-to-habitat conversation occurred over 13 years earlier when Sealab II aquanauts in the Pacific spoke n Conshelf III aquanauts in the Mediterranean on October 1, 1965.

Decompression from Neritica was achieved by raising the habitat vly to prescribed depths using an arrangement of chain blocks and kle. This same concept was used by the Poles during the Meduza gram in 1967-1968 and in the Rumanian LS-I program in 1970. The ompression time for Neritica from a saturation depth of 29 feet (9 m) 14 hours, with the habitat positioned such that the aquanauts ained at a depth of 9.9 feet (3 m) overnight. Considering that a nber of safe ascents have been made following saturation exposures at eet (7.9 m) with no decompression, a 14-hour decompression time n 29 feet (9 m) is extremely conservative.

eritica has been removed from the water and is located at the commer- port in Eilat awaiting its next mission.

COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Federal Republic of Germany/Israel	1977-1981	Eilat, Red Sea	9	2-3	16	L=3.4 W=2.0	3	Air	Shore	Readily movable	14	

PERMON



choslovakia, 1966-1967

ion was initiated by the Permon Diving Club of Ostrava, Czechoslovakia. endeavor was underfunded, ill equipped, and achieved only through personal dedication and risk of the divers themselves.

Permon I was a series of experiments conducted in 1966 in which fou subjects spent varying amounts of time in a hyperbaric chamber a simulated depths of about 50 feet (15.2 m) (Borovikov, 1968). The purpos of these experiments was to obtain medical data while undertaking th development of decompression procedures to be used in the open wate dives to follow. The details of these studies and the results are not known

The next phase of the program, referred to as Permon II, involved th construction and deployment of an underwater habitat. Following com pletion of construction in 1966, the habitat measured 6.6 × 6.6 feet (2.0 × 2.0 m) (Borovikov, 1968) and incorporated a double hatch system tha permitted decompression within the habitat. The life-support syster was designed to maintain two aquanauts for 3 days independent o surface support.

Permon II got off to a bad start. The plan called for the habitat to b placed in the Adriatic Sea at a depth of 82 to 98 feet (25 to 30 m) nea Ciovo, close to the Yugoslavian port of Split. It was the summer of 196 and the normally peaceful sea turned hostile. For 3 days, the suppor divers fought the waves, trying to protect the habitat. Eventually th cable linking Permon II to the shore snapped, and the habitat wa dragged into shipping lanes in the open sea. There was no choice but t open the ballast valves and sink the habitat (Podrazhanskiy, Rostarchul and Stephanov, 1973). The habitat was raised later, but the electric system was ruined and the operation was called off (Borovikov, 1968).

After 3 months of repairs, the habitat was returned to a reservoir a Bruntanya, Czechoslovakia (Fig. 9-21). In February 1967, the habit

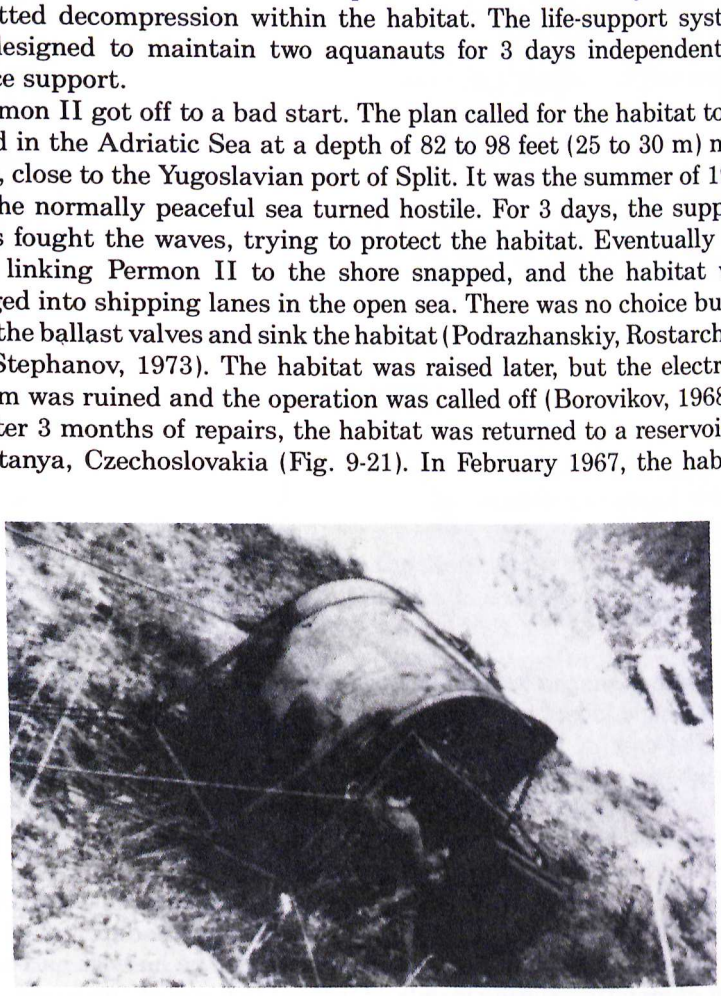


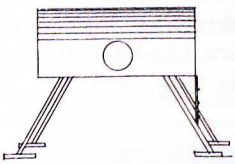
Figure 9-21. Permon II. *(From P. Borovikov, 1968, The Permon Program, Priro no. 7, p. 104.)*

(now referred to as Permon III) was ready to begin operations. Permon III was deployed under the ice from March 3-5, 1967, at a depth of 32.8 feet (10 m). The surface support team stayed in tents nearby on shore in weather that offered icy wind, rain, and snow. By contrast, the two aquanauts, Vilem Kospan and Vladimir Geyst, were comfortable on the bottom in the habitat where the temperature was a cool but tolerable 68°F (20°C), with humidity stabilized at 60%. During their 80 hours on the bottom, the two aquanauts made several excursions into the water, conducted medical tests, and tried out various nitrogen-oxygen breathing mixtures.

A second dive, Permon IV, was carried out in 1967 in which two aquanauts spent 100 hours at a depth of 82 feet (25 m). No further details of this program or any programs that may have followed are available.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Permon-II/III	Czech	1966 1967	Bruntanya	10	2	3	L=2.0 W=2.0	-	N_2/O_2	Shore	Readily movable	-	-

PORTALAB



United States, 1972

This mailbox-shaped habitat was designed by engineers at the University of Rhode Island in 1972 as an inexpensive, easy-to-handle research tool. The cost of the raw materials in 1972 dollars was only $1000. Portalab basically was a 6 × 7 × 8 foot (1.5 × 2.0 × 2.5 m) empty shell with benches, four ports, and an entrance trunk (Fig. 9-22). The steel shell weighed 2.4 tons and required about 7.2 tons of ballast when submerged. Power and breathing gas (air) were supplied from the shore.

The habitat was located at the campus of the University of Rhode Island in Narragansett Bay where it was emplaced at a depth of 37 feet (11.3 m). To maximize stability when under tow, the habitat had a low center of gravity, resulting in only 14 inches (35.6 cm) of freeboard. The initial launching was on September 30, 1972, but weather prevented

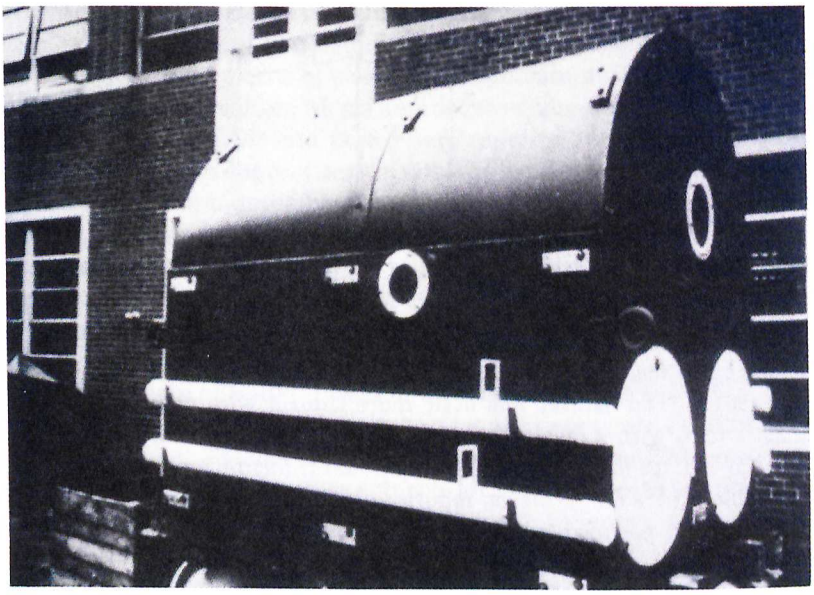


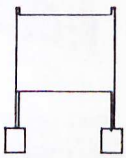
Figure 9-22. Portalab. *(Courtesy of University of Rhode Island, Kingston, Rhode Island.)*

immediate occupancy. The habitat was left on the bottom of the bay until October 3, when it was raised and towed to another site about 400 feet (122 m) from the campus pier. During towing, the legs and foot pads were removed and stored on the habitat. The design of Portalab was such that it "can be deployed anywhere in this area in a single day providing the weather is favorable" (Davis and Schenck, 1974, p.41).

Portalab was not designed for long occupancy, and no saturation dives were made in it. The habitat was used primarily for experiments on humidity and temperature control of habitat atmospheres, air flow, and related environmental control parameters. For example, it was planned to control humidity by lowering the dew point of the flushing air from the shore compressor. The habitat still is resting on the floor of Narragansett Bay (Davis and Schenck, 1974).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Portalab	U.S.A.	1972	Rhode Island	11.3	2	<1	L=2.4 W=1.8 H=2.1	7.2 Bal.	Air	Shore	Readily movable	0	-

ROBINSUB

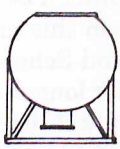


Italy, 1968

During the Tenth International Diving Sports Week in 1968 on the island of Ustica, Italy, a small habitat was submerged to a depth of 32.8 feet (10 m). The habitat was little more than a wire cage containing a plastic tent, with a displacement of 7.5 tons. An Italian, Italo Ferraro, lived in the hut for 48 hours. No additional information on Robinsub is available. There are, however, reports of a Robinsub II, which describe it as a light-permeable plastic enclosure that was used once with one occupant.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Robinsub-I	Italy	1968	Ustica Island	10	1	2	L=2.5 W=1.5 H=2.0	7.5 Displ.	Air	Shore	Readily movable	-	Wire cage/plastic tent

SADKO-I



Soviet Union, 1966

Sadko-I began about the same time as the Soviet Ikhtiandr program. (Sadko, an epic figure in Russian literature, was a Novgorod merchant who imagined that the sea kingdom was full of amazing wonders.) The habitat was designed and built by the Underwater Research Laboratory of the Leningrad Hydrometeorological Institute in conjunction with the Acoustics Institute of the Soviet Academy of Sciences (Dzhus and Mayer, 1967). It was a metal sphere 9.8 feet (3 m) in diameter designed to

hold two people. To increase the rigidity of the sphere, a second shell was installed consisting of two truncated cones. Sadko-I contained two cots, two desks, various pieces of scientific and monitoring equipment, and a single port for observation. Meals were delivered from the surface (Deryugin and Dzhus, 1971). Air and power were supplied from the support ship *R/V Nerey* or from shore. Once on site, the habitat was winched down to the desired depth using a block and tackle attached to an anchor on the seafloor, with air being added as needed to compensate for the increased pressure. Sadko-I was used in midwater rather than resting on the seafloor, as was the case in almost every other habitat program. It could be placed at depths ranging from 32.8 to 131.2 feet (10 to 40 m) (Diomidov and Dmitriyev, 1969).

The first tests of Sadko-I were in the summer of 1966 in the Black Sea off the Caucasian coast, where the habitat was moored at a depth of 137.8 feet (42 m) about 394 feet (120 m) offshore. The first aquanauts were a dog and two rabbits who served as subjects for 2 days in the habitat at depths ranging from 32 to 130 feet (9.8 to 39.6 m). Following the successful completion of these preliminary trials, the habitat was winched to a depth of 39.4 feet (12 m), where several teams of two aquanauts each spent 6 hours inside. Physiological data on the aquanauts were obtained while they made current measurements at depths ranging from the saturation depth to the seafloor. At the end of the mission, each team of aquanauts swam to the surface and decompressed in a DDC (Deryugin and Dzhus, 1970).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Sadko-I	USSR	1966	Black Sea, Sukumi Bay	12	2	6 hrs/ team	D=3 sphere	13.5	Air	Ship shore	Readily movable	-	Stationed in mid-water

SADKO-II

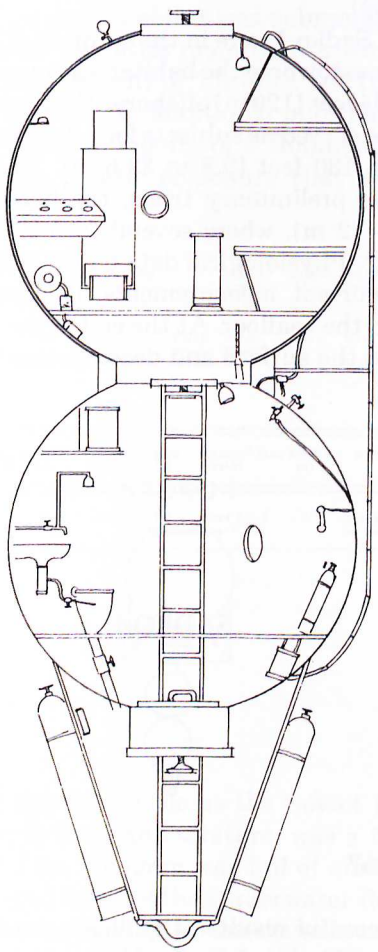


Soviet Union, 1967

Following the successful results of Sadko-I, the same group of specialists built an improved habitat, Sadko-II, in summer of 1967 and tested it that same year in the Black Sea.

Sadko-II consisted of two 9.8-foot (3 m) diameter double-hull steel spheres joined together by a flange containing a watertight hatch (Fig. 9-23*A*). The upper sphere was covered with a layer of rubber and was designed for habitation by two aquanauts. The lower sphere contained the entrance and storage space (Deryugin and Dzhus, 1970). An interesting feature was that the space between the two hulls of the lower sphere was filled with freshwater for use by the aquanauts. Accommodations in the upper sphere included two bunks, a dehumidifier, a fan for circulation, and a vacuum cleaner for use as a filtration unit. Food was provided from the surface.





A

Figure 9-23. *A*: Schematic of Sadko-II. *(After A. Mayer, V. Dzhus, and A. Ignat'yev, 1968, Sadko-2 Underwater Laboratory, Sudostroyenie* ***5:****31.)*

Sadko-II was launched from shore, after which about 7.5 tons of ballast were added while it was towed to the site (Fig. 9-23*B*). Once on site in Sukhumi Bay, it was winched down to the desired depth with the aid of a large 21-ton clump on the seafloor, where it was stationed in midwater in the same manner as Sadko-I. Surface support again was provided by the R/V Nerey, although most of the support team stayed on shore in a tent base camp, similar in some respects to the Tektite base camp in the U.S. Virgin Islands in 1969-1970.

During the summer of 1967, two aquanauts, Veniamin Merlin and Nikolay Nemtsev, spent 6 days at a depth of 82 feet (25 m). During the mission, a storm blew up and all but wiped out the tent city on shore. Fortunately, the habitat was unaffected, and the mission was completed as planned. In fact, the condition of the aquanauts was better than that of the support team on shore (Sergeyev, 1968). The double-hulled walls kept the inside temperature at a comfortable 75.2°F (24°C). The aquanauts performed a number of oceanographic studies and made descending excursions to depths up to 148 feet (45 m).

On completion of the six-day mission, Sadko-II was sealed, brought to the surface, and towed to a protected area, where the aquanauts underwent the 70-hour decompression inside.

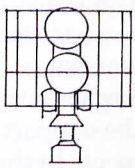
NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Sadko-II	USSR	1967	Black Sea, Sukumi Bay	25	2	6	D=3 2 spheres	28.5 Bal.	N_2/O_2	Ship shore	Readily movable	70	Stationed in mid-water



B

Figure 9-23. *B*: Sadko-II. *(After Sergeyev, S., 1967, Sadko's Visitor from Leningrad. Izvestiya* **15:**4, in *Foreign Science Bulletin, 1967, Aerospace Tech. Div., Library of Congress, Washington, D.C., 3, No. 11, 53.)*

SADKO-III



Soviet Union, 1969

Sadko-III was a continuation of the work of the Leningrad Hydrometeorological Institute. The habitat consisted of three vertically arranged cylindrical chambers connected by airtight hatches, the upper two of which were the Sadko-II habitat with major modifications (Fig. 9-24). The total height was 49.2 feet (15 m), 23 feet (7 m) higher than Sadko-II. The upper compartment contained a control panel and the main life-support systems. The middle section was the living compartment, and

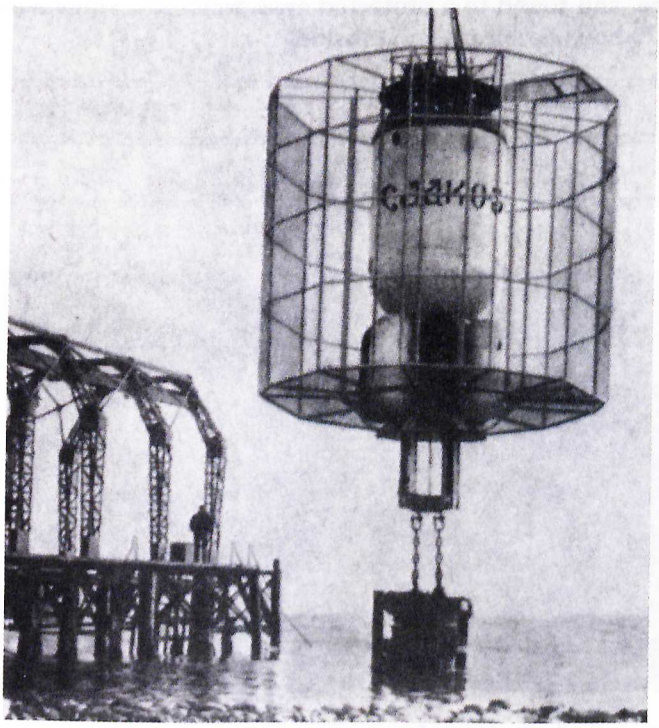


Figure 9-24. Sadko-III (*From R. Forster, 1971, Das Unterwasserlabor Sadko-3. Poseidon* ***109:***33).

the lower compartment housed a hot shower, a toilet, and storage cabinets and served as the decompression chamber. The dry weight now was 15 tons, and with the necessary ballast the habitat weighed 45 tons (Stepanov, 1969). The inside was more comfortable, furnished with better bunks, portholes, and a working office. The breathing mixture was composed of nitrogen, helium, and oxygen (percentages not included in reference).

In the fall of 1969, the habitat was used in Sukhumi Bay. It was winched into position so that the saturation depth was 82 feet (25 m). A preliminary mission lasting 3 days was carried out by three aquanauts (Chernov, 1970). The objectives were to test all systems, to conduct bioacoustic studies, and to obtain medical data on the three aquanauts. A special open-air cage consisting of a metal framework covered by a capron (nylon) net was constructed to permit observing and recording of fish sounds. This enclosure had a volume of about 10,500[3] feet (300 m^3), and fish could move within it under nearly natural conditions.

After the 3 days on the bottom, the three aquanauts, V. Dzhus, D. Rumyantsev, and A. Monkevich, were transferred to a diving bell that had been lowered next to the habitat. The bell was raised to the surface and taken to a shore decompression chamber, where the aquanauts were transferred and decompressed.

Following these preliminary tests, a 14-day mission was conducted by three aquanauts. The objectives of this mission were the further evaluation of the habitat as a seafloor laboratory, the improvement of the communications system, and additional medical research. Further studies of fish behavior also were carried out, including extensive recording of fish sounds (Deryugin and Dzhus, 1970).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Sadko-III	USSR	1969	Black Sea Sukumi Bay	25	3	14	D=3.0 H=15.0	30 Bal.	He/N_2/ O_2	Ship	Readily movable	-	Stationed in mid-water

SELENA-I



Soviet Union, 1972

Selena-I is considered to be the first of three development stages in what is termed the Selena program. The ultimate goal was to develop a

group of underwater habitats, fully autonomous over a long period of time. At the outset, two specific tasks were envisaged: to develop an underwater habitat from a thin, cheap, strong, transparent, and light polymer film that would be permeable to carbon dioxide and oxygen molecules and to develop an air treatment system for such a habitat, using the same polymer film, thus making the envelope and the similar air treatment system part of a passive air-regeneration system.



Figure 9-25. Selena-I. *(After A. Novokhatnyy, 1973, Selena-1 Underwater Habitat, Sportsmen-Podvodnik* ***35:****56.)*

The inflatable envelope consists of a 0.3 mm-thick polymer film (possibly polytetrachlorethylene) developed by Dr. V. Ye. Gul', a professor of chemistry at the Moscow Technological Institute of the Meat and Dairy Industry. The envelope is gas permeable to oxygen and carbon dioxide. Selena's chief developer was Alexander Novokhatnyy, a sports diving instructor for the Del'fin Diving Club in Moscow (Frantsen, 1974).

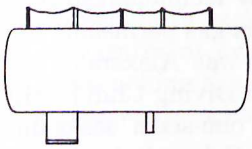
Following tests of a one-sixth scale model, the full-sized Selena-I habitat was deployed in Beloye Lake, located about 112 miles (180 km) from Moscow, in the summer of 1972 at a depth of 37.7 feet (11.5 m) (Fig. 9-25). The entire effort lasted 25 days, including set-up, assembly, and deployment. The membrane was contained inside a system of nets anchored to a metal frame 16.4 feet (5 m) in diameter, which in turn was connected to corkscrew anchors. The total lifting capacity was about 5 tons. Selena-I was 6.6 feet (2 m) in diameter, about 9.8 feet (3 m) high, and with a volume of 177 ft^3 (5 m^3). The first diver to test the new system was Boris Kats, who spent 15 hours in the habitat. During this time, he performed certain system checks, habitat structure checks, and several equipment assembly test tasks.

The second stage of the program called for the development of Selena-II a 3531 ft^3 (100 m^3) habitat with a planned deployment date of summer 1974. The habitat was to be mounted on a caterpillar-tread platform to provide bottom mobility.

The third phase of the Selena program involved the development of an artificial gill life-support system using the gas-permeable polymer film. According to Novokhatnyy (1973), Novokhatnyy's group designed and built a prototype and tested it in Beloye Lake in 1973. The gill itself was in the form of an accordion bellows. In the air-regeneration system tests, divers lying on the bottom exhaled into a transparent film balloon (size unknown). The gill system was then attached to the balloon. Water was circulated through the gill system by a propeller while the air was moved with a fan. The gill system alone is said to be about the size of a shoe box. The auxiliary systems were somewhat larger and were to be reduced in size in the future. Air samples (approximately 1½ to 2 liters in volume) were taken regularly and sent to Moscow for analysis. The tests showed that over a 3-hour period, the air quality in the balloon had improved by six times. Further details of this intriguing program are not available.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Selena-I	USSR	1972	Beloye Lake	11.5	1	15 hrs.	D=2.0 H=3.0	5	Air	-	Readily movable	-	Semi-permeable membrane

SHELF-I



Bulgaria, 1970

The Shelf-I habitat was designed and built by the Institute of Oceanology in Varna with the cooperation of the fishing industry and several other organizations. This 8.2 × 19.7 foot (2.5 × 6 m) cylindrically shaped structure was divided into three compartments: a wet room containing the entrance trunk, the living quarters, and a working room (Fig. 9-26). The basic structure was attached to a foundation for stability and ballast,

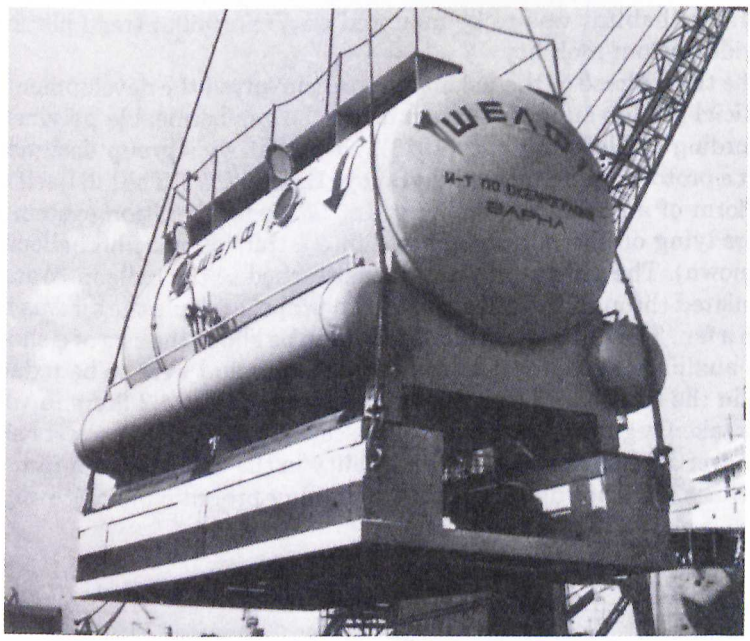


Figure 9-26. Shelf-I. *(Courtesy of Institute of Oceanology, Varna, Bulgaria.)*

which resulted in a total weight of 30 tons. The habitat contained the necessary accommodations for living underwater, including communications, television, and the basic life-support equipment to support a crew of three (Cherenko, 1971). Power and air were supplied by the support ship, which also had the necessary instrumentation for controlling the habitat temperature, water level, and air pressure. In most other habitats, these controls were managed by the aquanauts in the habitat.

Prior to the open-water phase of the program, test runs were made in a hyperbaric chamber for the purpose of selecting the aquanauts. Eight candidates each spent 6 hours at 33 feet (10 m), as well as 6 hours, 24 hours, and 48 hours at 99 feet (30 m). The decompression time from the 99-foot exposures was 36 hours. Based on performance during these trials, plus the results of the medical examinations, six aquanauts were selected. This appears to be the only occasion on which aquanauts were selected based on actual saturation exposures.

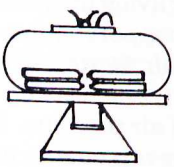
The first three aquanauts to use Shelf-I entered the habitat on August 28, 1970, following its emplacement in Burgas Gulf in the Black Sea at a depth of 65.6 feet (20 m). The breathing gas was air. The inside temperature of the habitat was maintained at the same temperature as the surrounding water, 75.2°F (24°C). Habitat humidity was kept at 90 to 95%, typical of many other early habitats. Vertical excursions were made upward to a depth of 44 feet (13.4 m) and downward to a depth of 87 feet (26.5 m). Several marine science studies were carried out, including dissolved oxygen measures, bottom surveys, and some experiments using stereo cameras (Miller, 1974; Anon., 1971).

Following 4½ days on the seafloor, the three aquanauts entered a diving bell and were transferred to the surface, where the bell was mated to a DDC. Decompression was carried out in the deck chamber and lasted 33.5 hours. During the 4-day mission, which ended on September 1, each aquanaut averaged about three or four 30-minute dives per day. A second mission was begun on September 2, 1970, but was aborted after 3 days due to bad weather. The profile and activities during this mission essentially were the same as the first mission.

The habitat was not used again and is now resting in front of the Oceanographic Research Institute in Varna (Miller, 1974).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Shelf-I	Bulgaria	1970	Burgas Gulf	20	3	4-5	L=6.0 D=2.5	30	Air	Ship	Readily movable	33.5	-

SPID



United States, 1964, 1974

The SPID (Submersible Portable Inflatable Dwelling) habitat was used for two missions. In the first, Link's 1964 Man-in-the-Sea II program, the habitat was secured on the seafloor at a depth of 430 feet (131 m) for 24 hours. A description of this project and the details of the SPID habitat are contained in Chapter 3 (Figs. 3-8, 3-9).

On May 12-13, 1974, SPID was used once again as a seafloor shelter for a saturation dive. Whereas in 1964 the site was the warm waters of the Mediterranean, this time SPID was located in Resolute Bay, Cornwallis Island, in the Canadian Northwest Territory under 6.6 feet (2.0 m) of ice. The occasion was a program called Arctic IV sponsored by the James Allister MacInnis Foundation. The principal diving objective of this program was to determine the feasibility of using shallow air-saturation diving methods in remote under-ice regions and to compare the results with those found in Newfoundland when using the LORA habitat (English 1974*a*).

During Arctic IV, James G. English of the Memorial University of Newfoundland and Robert Wicklund, employed at that time by Perry Oceanographics, spent 24 hours at a depth of 14 feet (4.3 m) in the SPID habitat. Both aquanauts previously had saturated in the LORA habitat in Newfoundland.

Prior to the start of Arctic IV, an unsuccessful attempt was made to ballast SPID using two explosive anchors, each designed to provide 10,000 pounds of hold-down tension. Unfortunately, the flukes of both anchors broke when as little as 300 pounds of upward pull was applied. The problem of anchoring was solved by making the inflatable SPID positively buoyant such that it was pressed up against the underside of the ice cover (MacInnis, 1976). The preparation of the structure and the installation and testing of the rest of the life-support system required 9 diving man-hours.

Although the water temperature was 28.5°F (-1.9°C) the inside temperature of the habitat was maintained at a comfortable 80.6°F (27°C).

During the 24-hour saturation, the aquanauts spent 11.8 man-hours in the water during the nine excursions each made. The maximum depth attained during these excursions was 52.5 feet (16 m). Work tasks were based on 40-minute excursions followed by 60- to 90-minute rest periods. During the excursions the aquanauts wore variable-volume neoprene rubber dry suits, which provided excellent thermal protection. Each diver also was equipped with two completely independent air supplies in a double pack. The primary regulator was a double hose unit, with an antifreeze-equipped single hose unit as a backup.

The dive went as scheduled, and accomplished major dive objectives. Cold discomfort was most evident in the hands. Table 9-2 summarizes the Arctic IV saturation dive. The actual dive closely approximated the predive plan. The decreased saturation depth was due to the failure of the anchors, which resulted in the SPID's being pressed against the underside of the ice cover.

According to MacInnis, the project director, "At the conclusion of the twenty-four hour dive, both divers were fatigued due to lack of sleep but the general consensus was that safety and efficiency were not compromised" (MacInnis, 1976, p. 199).

Following the 1974 Arctic IV project, SPID was given to Seneca College of Applied Arts and Technology in King City, Ontario, Canada.

Table 9-2. Summary of SPID Arctic IV Dive

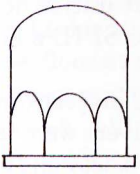
Relevant Parameters	*Proposed*	*Actual*
Overall task accomplishment	60-90%	85%
Water Temperature (°C)	1.0 max	-1.9
		(28.6°F)
Interior habitat temperature (°C)	15.5 min	27.0
		(80°)
Core temperature variation (°C)	1.5	N.A.
Saturation depth (m)	8.0	4.3
Excursion depth (m)	16.0	16.0
Total duration (hr)	24.17	24.17
Number of excursions per man	13	9
Total excursion duration (hr/man)	8.7	6.6
Mean excursion time (min/man)	40	43.8
Mean habitat time (min/man)	71.5	117.3
Excursion duration % (dive duration)	35.9%	27.3%

Source: From J. English, 1975, Shallow Air Saturation Dive in the High Arctic, in *Ocean '75*, IEEE Publication 75 CHO 996, San Diego, Calif., Dec. 1, p. 266. Copyright © 1975 by the Institute of Electrical and Electronics Engineers, Inc.

Subsequently it was used as a diver training facility in Lake Seneca at a depth of 20 feet (6.1 m) until its removal in the late 1970s (Landry, pers. commun.). It is now in retirement at Seneca College, along with the Sub-Igloo and Sublimnos habitats.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
SPID (Man-in-Sea II)	U.S.A.	1964 1974	Bahamas, Canadian Arctic	131.7 4.3	2	1	L=2.4 W=1.2	-	90.8% He 5.6% N_2 3.6% O_2	Ship shore	Readily movable	92 0	Inflatable habitat

SPRUT

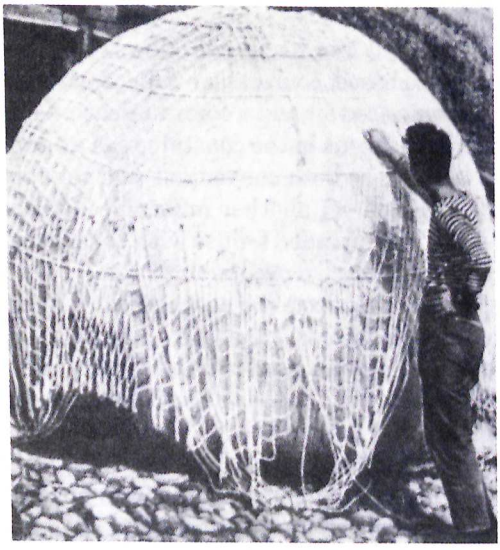


Soviet Union, 1966–1970

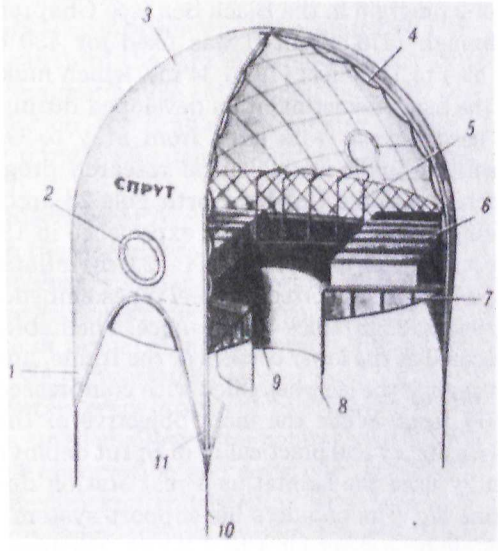
During 1966, Soviet specialists designed and constructed Europe's first pneumatic seafloor habitat (Korolev et al., 1971). An inflatable habitat also had been used by Edwin Link in 1964 during his Man-in-Sea II program and again in the Arctic in 1974. The Soviet habitat, Sprut (meaning "octopus"),was made of a rubberized fabric reinforced on the outside to prevent overfilling and rupture. It was hemispherical in shape, with anchor lines running downward from the floor (Dzhafarov, 1967). When inflated, it had the appearance of a jellyfish and had a useful area of 32.3 feet^2 (3 m^2). The habitat was equipped with a diver access trunk, view ports, a telephone, and instrumentation for oceanographic research. This early version of Sprut was referred to in the German literature as Oktopus and/or Krake.

Sprut was first tested in July 1967 near the Karadag Biological Station on the Black Sea. In deploying the dwelling, scuba divers towed the habitat to the site and fastened the anchor lines. When all lines were in place, the habitat was inflated with air pumped from a compressor on shore. One Soviet publication states that Sprut could be deployed in 80 minutes (Yelenskiy, 1969). During the first test, the three designers lived and worked in the Sprut for 14 days.

In 1968 a second inflatable habitat, designated Sprut-M, was designed and constructed. This tear-shaped version was 7.9 feet (2.4 m) in diameter and had double walls (Fig. 9-27A), one a gas-impermeable envelop of



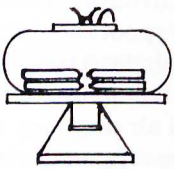
A



B

Figure 9-27. *A*: Sprut-M; *B*: Sprut-U. *(From A. Korolev, V. Shabalin, V. Murav'yev, and N. Aybulatov, 1971, Sprut-U Inflatable Underwater Habitat, Sudostroyeniye* ***9:****24, 25.)*

SPID



United States, 1964, 1974

The SPID (Submersible Portable Inflatable Dwelling) habitat was used for two missions. In the first, Link's 1964 Man-in-the-Sea II program, the habitat was secured on the seafloor at a depth of 430 feet (131 m) for 24 hours. A description of this project and the details of the SPID habitat are contained in Chapter 3 (Figs. 3-8, 3-9).

On May 12-13, 1974, SPID was used once again as a seafloor shelter for a saturation dive. Whereas in 1964 the site was the warm waters of the Mediterranean, this time SPID was located in Resolute Bay, Cornwallis Island, in the Canadian Northwest Territory under 6.6 feet (2.0 m) of ice. The occasion was a program called Arctic IV sponsored by the James Allister MacInnis Foundation. The principal diving objective of this program was to determine the feasibility of using shallow air-saturation diving methods in remote under-ice regions and to compare the results with those found in Newfoundland when using the LORA habitat (English 1974*a*).

During Arctic IV, James G. English of the Memorial University of Newfoundland and Robert Wicklund, employed at that time by Perry Oceanographics, spent 24 hours at a depth of 14 feet (4.3 m) in the SPID habitat. Both aquanauts previously had saturated in the LORA habitat in Newfoundland.

Prior to the start of Arctic IV, an unsuccessful attempt was made to ballast SPID using two explosive anchors, each designed to provide 10,000 pounds of hold-down tension. Unfortunately, the flukes of both anchors broke when as little as 300 pounds of upward pull was applied. The problem of anchoring was solved by making the inflatable SPID positively buoyant such that it was pressed up against the underside of the ice cover (MacInnis, 1976). The preparation of the structure and the installation and testing of the rest of the life-support system required 9 diving man-hours.

Although the water temperature was 28.5°F (-1.9°C) the inside temperature of the habitat was maintained at a comfortable 80.6°F (27°C).

During the 24-hour saturation, the aquanauts spent 11.8 man-hours in the water during the nine excursions each made. The maximum depth attained during these excursions was 52.5 feet (16 m). Work tasks were based on 40-minute excursions followed by 60- to 90-minute rest periods. During the excursions the aquanauts wore variable-volume neoprene rubber dry suits, which provided excellent thermal protection. Each diver also was equipped with two completely independent air supplies in a double pack. The primary regulator was a double hose unit, with an antifreeze-equipped single hose unit as a backup.

The dive went as scheduled, and accomplished major dive objectives. Cold discomfort was most evident in the hands. Table 9-2 summarizes the Arctic IV saturation dive. The actual dive closely approximated the predive plan. The decreased saturation depth was due to the failure of the anchors, which resulted in the SPID's being pressed against the underside of the ice cover.

According to MacInnis, the project director, "At the conclusion of the twenty-four hour dive, both divers were fatigued due to lack of sleep but the general consensus was that safety and efficiency were not compromised" (MacInnis, 1976, p. 199).

Following the 1974 Arctic IV project, SPID was given to Seneca College of Applied Arts and Technology in King City, Ontario, Canada.

Table 9-2. Summary of SPID Arctic IV Dive

Relevant Parameters	*Proposed*	*Actual*
Overall task accomplishment	60-90%	85%
Water Temperature (°C)	1.0 max	-1.9 (28.6°F)
Interior habitat temperature (°C)	15.5 min	27.0 (80°)
Core temperature variation (°C)	1.5	N.A.
Saturation depth (m)	8.0	4.3
Excursion depth (m)	16.0	16.0
Total duration (hr)	24.17	24.17
Number of excursions per man	13	9
Total excursion duration (hr/man)	8.7	6.6
Mean excursion time (min/man)	40	43.8
Mean habitat time (min/man)	71.5	117.3
Excursion duration % (dive duration)	35.9%	27.3%

Source: From J. English, 1975, Shallow Air Saturation Dive in the High Arctic, in *Ocean '75*, IEEE Publication 75 CHO 996, San Diego, Calif., Dec. 1, p. 266. Copyright © 1975 by the Institute of Electrical and Electronics Engineers, Inc.

rubberized Kapron (nylon) and the other a double-layer, folded-over Kapron net. The walls contained two plastic windows. The habitat again was inflated from a shore-based compressor. Sprut-M contained an emergency supply of compressed air and a communication system to shore. It was used for brief expeditions in the coastal areas at depths up to 46 feet (14 m) and was found to be both convenient and reliable.

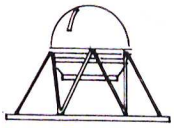
In 1968 work began on yet another inflatable habitat, referred to as Sprut-U. This model was intended for use with the Chernomor-2 program in the Black Sea. The project moved along rapidly. By March 1969 the plan was completed, and by June the new habitat had been constructed. Sprut-U also had double-layered walls, the outer providing strength and the inner as a heat insulator and impermeable membrane (Fig. 9-27B). It contained two view ports, a 3.3 foot (1.0 m) entrance trunk, an inflated mat on the floor, and two inflatable cots. Unlike the previous models in which a trawl net was used for anchoring the habitat, Sprut-U used a parabolic belt with lines running upward through hoses and intersecting on the top of the outer wall. Air was supplied from an external compressor, although emergency air was available.

During 1969 Sprut-U was used for a series of experiments and housed from one to four aquanauts at a time. After these experiments were completed, Sprut-U was used as a shelter at a depth of 82 feet (25 m) for the Chernomor-2 program in the Black Sea (see Chapter 4). During the years 1969 through 1970, Sprut-U was used for 430 days at depths ranging from 39.4 to 111.5 feet (12 to 34 m), which makes it one of the most used of the many Soviet habitats developed during that period.

Sprut was used several years later, from May to October 1977, in conjunction with an under-ice biological research program performed during the operation of the USSR's North Pole-23 arctic drift station. Perhaps profiting from the SPID arctic experience in 1974, the Soviets rigged the 8-foot diameter, 6-foot high (2.4 × 2.0 m) inflatable hemisphere to a square metal frame supported by steel pipes embedded about 2 feet (50 cm) in the 9-foot (2.5m) thick overhead ice. The habitat containment netting was secured at the lower corners of the frame, and the top of the habitat rested against the ice when filled with compressed air during the September 1977 tests. While the main objective of the effort was to determine the feasibility and practicality of Sprut deployment under ice, divers apparently used the habitat as a rest station during studies of under-ice marine life. The habitat's life-support system was said to be capable of sustaining a diver for 4 to 6 hours. Because of the shallow depth in this arctic program, saturation diving techniques were not used (Mel'nikov and Murav'yev, 1978).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Sp[illegible]ut (Octopus)	USSR	1966–1970	Black Sea	10.5	3	14	D=5.0 sphere	-	Air	Shore	Readily movable	-	Inflatable habitat
Sp[illegible]ut-M	USSR	1968	Black Sea	14	2	-	D=2.4	-	Air	Shore	Readily movable	-	Inflatable habitat
Sp[illegible]ut-U	USSR	1969–1970	Black Sea	12–34	1–4	-	-	-	Air	Shore	Readily movable	-	Inflatable habitat

SUB-IGLOO



Canada, 1972–1975

The Arctic III Sub-Igloo habitat program was conducted farther north and in the most inhospitable environment of all of the world's undersea habitat endeavors. The location was in Resolute Bay, Canada, almost 600 miles (965 km) north of the Arctic Circle and only 125 miles (201 km) from the north magnetic pole (MacInnis, 1973). To add to the already challenging situation, the time was November—December 1972, which meant that the project was carried out in the perpetual darkness of a polar winter.

The overall objectives of Arctic III, directed by Dr. Joseph MacInnis, were to evaluate the usefulness of a seafloor station in arctic waters, to determine the necessary surface support for such operations, to conduct biological and geological studies of the surrounding area, and to evaluate the performance of humans and equipment in the hostile environment (Stang, 1974). Air temperatures ranged from minus 30° to 50°F (−34 to 45°C) with water temperatures of 28.5°F (−1.9°C).

Sub-Igloo is a small shallow-water habitat built in 1972 to serve primarily as a seafloor observation and emergency station beneath a layer of arctic ice. Its design and construction were sponsored by the James Allister MacInnis Foundation of Toronto, Canada. The main structure is a clear 3/4-inch (1.9 cm) thick acrylic sphere 8.2 feet (2.5 m) in diameter and formed by joining two hemispheres together with an aluminum ring

around the equator (Elsey, 1974). This ring is attached by sixteen adjustable struts to a ballast tray loaded with 8 tons of iron pigs to achieve the necessary negative buoyancy. Divers enter through a 39-inch (99 cm) opening cut in the bottom of the lower hemisphere. Once inside, the diver can sit on the benches provided around the sides. The 360° clear acrylic provided a spectacular view of the surrounding water (Fig. 9-28). In many ways it resembles the Bubble habitat built in England in 1966. It had been determined from two earlier expeditions that the structure required for the Arctic III expedition should be fully portable and easily assembled by divers working in darkness and in zero visibility.

Prior to arriving in the arctic, three freshwater trials were held in Georgian Bay to familiarize the expedition members with the underwater assembly methods. These trials were conducted in water temperatures ranging from 50° to 59°F (10° to 15°C) with the divers wearing the same

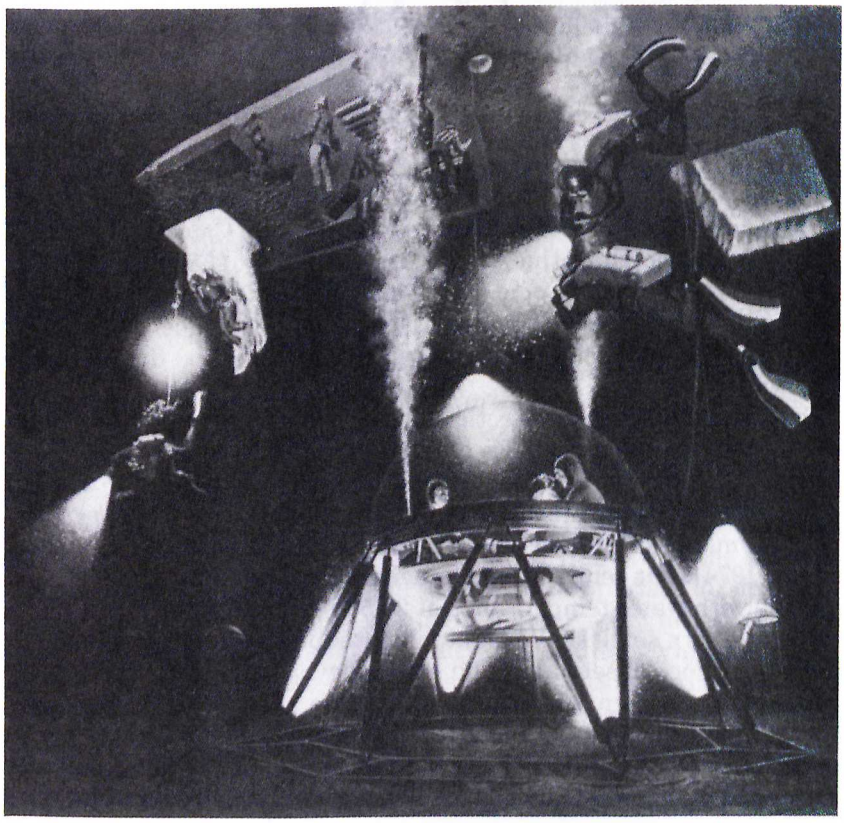


Figure 9-28. Sub-Igloo. *(By Davis Meltzer; © 1973 National Geographic Society.)*

equipment to be worn in the arctic. It was confirmed that Sub-Igloo could be assembled easily underwater by four divers. The habitat was to serve as a refuge station on the floor of Resolute Bay at a depth of 40 feet (12.2 m).

Once the site was selected, an 8 × 10 foot (2.4 × 3.0 m) hole was cut through the 3-foot (0.9 m) thick ice cover to lower the habitat into the water. Eight tons of ballast were dropped to the seafloor, and the habitat was lowered by sections, to be reassembled by the divers on the bottom. Diving operations were conducted from a heated tent set up on the surface of the ice (Fig. 9-28). Divers wore variable-volume dry suits for added protection against the cold water, which provided a layer of air between the inner surface of the neoprene rubber and the wool underwear worn underneath. Physiological measurements were made on the divers while they were in the water, including recordings of core temperature and heart rate. The data revealed that the divers experienced a relatively small loss of body heat during the operation (Andersen, 1974). This was attributed to the effectiveness of the variable-volume dry suits. Although visibility was in excess of 100 feet (30.5 m) unless the bottom silt was disturbed, lateral excursions were limited to a distance that could be covered by one breathhold from Sub-Igloo for safety reasons.

An interesting feature of diving under the ice is the ability to walk upside down when wearing an inflatable diving suit. It is a strange experience indeed to shuffle along head down with bubbles rising to your feet. An underwater loudspeaker was installed to permit the diving supervisor to talk to the divers. Extensive underwater lighting was used for safety and for filming the progress of the program.

After 5 days in operation, Sub-Igloo was disassembled by two divers in approximately 4 hours. While over 200 dives were made, the most impressive accomplishment was the successful installation and use of the habitat as an undersea work station and the knowledge gained of diving operations in the arctic. It was concluded by Douglas Elsey (the project engineer) that

> the structure, as an observation platform, cannot be surpassed. The diver has a complete and panoramic view of the environment. The marine biologist is offered a unique tool for unlimited observation. The structure also can be used as a control centre for the direction of underwater operations. In clear arctic waters, a transparent acrylic sphere allows observers to see the status of all working divers. [Elsey, 1974, p.76].

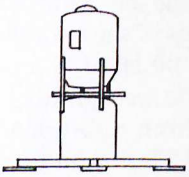
Sub-Igloo was used again in Resolute Bay in the Canadian arctic for 2 months in 1974 during the Arctic IV program as a seafloor work station (MacInnis, 1976). In this instance, it served in support of an under-ice saturation diving program involving the SPID habitat designed and

built by Edwin Link. Sub-Igloo also was used in the Caribbean as an emergency seafloor station for project SCORE in 1975.

Sub-Igloo still is intact and since 1975 has been in storage at Seneca College of Applied Arts and Technology, King City, in Ontario, Canada. According to Dr. MacInnis, there is a good possibility it will be used in the Philippines in the future (MacInnis, pers. commun.).

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Sub-Igloo	Canada	1972-1975	Cornwallis Island	12.2	2-4	1	D=2.5 sphere	8 Bal.	Air	Shore	Readily movable	0	Under ice

SUBLIMNOS



Canada, 1969

Sublimnos (meaning "under freshwater") is a shallow-water habitat built as a shelter for budget-limited scientists. Referred to as the Volkswagen of habitats, it cost Can$15,000 in 1969. Sublimnos provided day-long work capability for one or two divers for periods of 6 to 8 hours (Quig, 1969). It was a vertically oriented cylinder 9 feet (2.7 m) high and 8 feet (2.4 m) in diameter, with approximately 350 feet^3 (9.9 m^3) of living space (Fig. 9-29). Access is through a 35-inch (89 cm) hatch in the floor of the personnel (upper) chamber. The habitat contained an observation bubble on top and four acrylic ports in the vertical cylinder. The interior was furnished with dropleaf tables and stools, and because it was designed to operate in cold water, Sublimnos was insulated inside with a sprayed polyurethane. Breathing air was supplied by a compressor located either on shore or on a support ship. The original design did not include a heating or dehumidifying system.

The habitat, developed by Dr. Joseph MacInnis, was first launched on June 24, 1969, at a depth of 33 feet (10.1 m) about 250 feet (76.2 m) offshore in Little Dunk's Bay on the Bruce Peninsula in Georgian Bay near Tobermory, Ontario, Canada (MacInnis, pers. commun.). The origi-

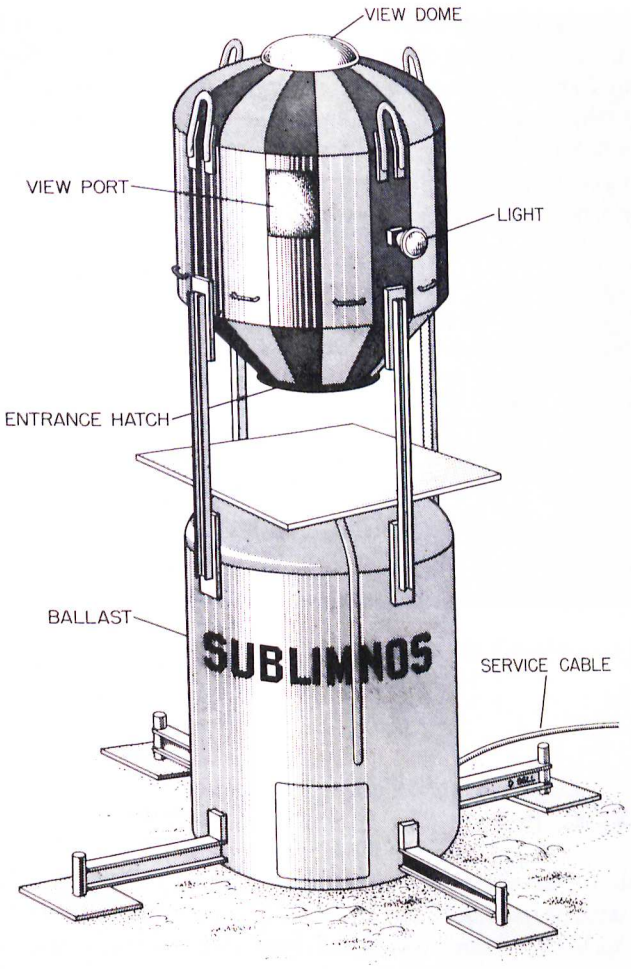


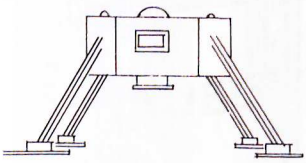
Figure 9-29. Sublimnos. *(Copyright © 1969 by the Great Lakes Foundation; courtesy of Great Lakes Foundation, Ann Arbor, Michigan.)*

nal plan called for it to be used in that location for 2 years (Quig, 1969). At that time scientists from the University of Michigan conducted marine scientific experiments and evaluated that habitat as a research tool (Somers and Anderson, 1970). A 50-foot (15.2 m) research vessel was used as a support platform. During a five-day period, divers from the University of Michigan spent more than 100 man-hours underwater. Following the extensive experiments carried out, it was concluded that the Volkswagen approach to seafloor habitats had a lot to offer. In 1975, Sublimnos was

donated by the MacInnis Foundation to Seneca College of Applied Arts and Technology in King City, Ontario, Canada. It was retrieved from Georgian Bay by Seneca trainee divers and taken to the King City campus, where it was refurbished and installed in Lake Seneca at a depth of 28 feet (8.5 m). It was used as a diver training and support facility until its removal. At the time of publication, it was undergoing a refit and was expected to be reinstalled in a nonsaturation mode (Landry, pers. commun.). Both the SPID and Sub-Igloo habitats also are located at Seneca College.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Sublimnos	Canada	1969-	Georgian Bay, Ontario	10.1	2-4	up to 24 hrs.	H=2.7 D=2.4	9	Air	Ship shore	Readily movable	-	Designed for day long occupation

SUNY-LAB-I



United States, 1976

Suny-Lab was developed and constructed over a 4-year period by engineering students at the Stony Brook Campus of the State University of New York under the direction of Professor Herbert Herman. The habitat was developed as a student engineering project, as was Edalhab at the University of New Hampshire, to provide a means of making extended observations in nearby waters.

The core of the habitat is a cement mixer surrounded by a hexagonally shaped cement shell to add needed ballast (Fig. 9-30). This provided an inside diameter of about 5 feet (1.5 m). Suny-Lab is supported by three steel legs fitted into channels welded to the inside steel cement mixer. There is an entrance at the bottom, a bubble on the top for observation, and small ports in the sides. Suny-Lab was designed to operate at depths to about 40 feet (12.2 m) and to permit observations for several hours at a time for two or three persons. Air is used as the breathing gas and is supplied from a surface-support boat. The life-support system also includes a CO_2 monitor, a CO_2 scrubber, and communications to the surface.

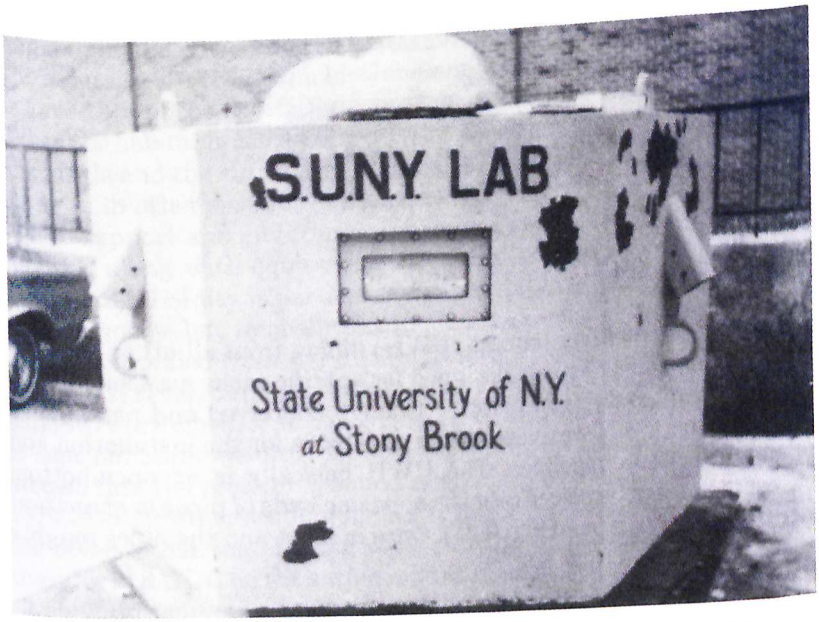


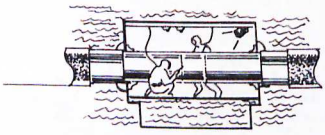
Figure 9-30. Suny-Lab. *(Courtesy of Steven C. Resler, Conservation Advisory Council, Smithtown, New York.)*

Suny-Lab has been used extensively following its initial trials in 1976. On May 12, 1978, it was positioned 1 mile north of Long Beach in Smithtown Bay, Long Island Sound, New York, at a depth of about 40 feet (12.2 m) (Resler, pers. commun.) for the first of a long series of observations of a nearby artificial reef. As of December 1978, over 21,000 automobile tires had been emplaced in an area approximately 450 by 1050 feet (137 by 320 m) in size. In addition to being used for the artificial reef program, Suny-Lab has been used to obtain other baseline data, such as water samples, core samples, and observation and collection of local plants and animals. Suny-Lab I is still in the waters of Smithtown Bay as of December 1983 (Herman, pers. commun.).

The successful use of Suny-Lab I stimulated interest in the construction of a second habitat (Suny-Lab II) that has been completed but not launched.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Suny-Lab	U.S.A.	1976-	New York	12.2	2-3	1	1.5	6	Air	Ship	Readily movable	-	Made from cement mixer

UNDERWATER WELDING HABITATS



United States, 1967–

The underwater welding habitat (UWH) differs from all other habitats described previously as it is designed for specific tasks associated with the offshore oil and gas industry. Although conceived and patented in 1954, the first UWH was used in the mid-1960s for the installation and repair of undersea pipelines. The UWH basically is an open-bottom enclosure that can be placed over the opposing ends of pipes or structural members needing repair (Fig. 9-31). Once in place and the pipes roughly

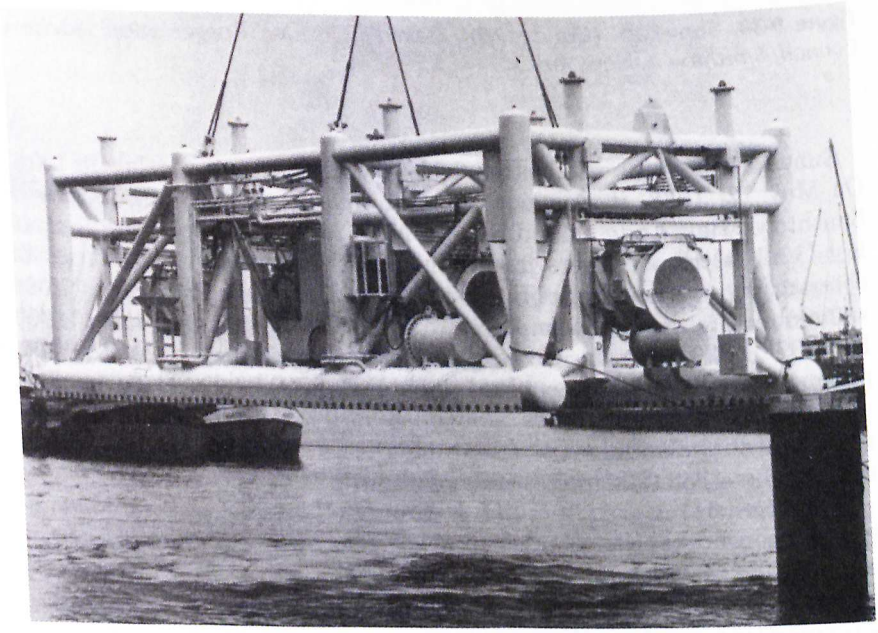


Figure 9-31. Submersible pipeline alignment rig (underwater welding habitat). *(Courtesy of Taylor Diving & Salvage Co., Inc.)*

aligned, divers enter and install seals at the intersection of the pipe and the habitat walls (Masubuchi, Gaudiano, and Reynolds, 1983). The water is forced out of the habitat by pumping in breathing gas from the surface. When the habitat is completely dewatered, the pressure differential between the inside and the surrounding water is about 2.5 psi, approximately the same as in other seafloor habitats.

Life-support and environmental control systems are contained in the habitat, along with equipment necessary to align and weld the pipes. Control of humidity is particularly important in achieving quality welds and cannot be left to chance as was the case with most other habitats. Power is supplied from the surface (Smith, 1983).

The UWH can be either full size, where the divers get out of diving gear and into work clothes, or the so-called minihabitat, where the diving gear is kept on. Some welding habitats are placed on the seafloor and evacuated so that the pressure inside is maintained at 1 atmosphere (Delaune, 1979). Unlike other seafloor habitats, the UWH is not designed to house the divers other than during work periods. If the divers are saturated, they live in a DDC on the surface and are transferred to and from the work site in a pressurized transfer chamber.

At the present time, full-size UWHs are about 10 feet (3 m) square and can handle pipes up to 54 inches (137.2 cm) in diameter (Masubuchi, Gaudiano, and Reynolds, 1983). Specially designed irregularly shaped habitats are used for repairing the diagonal and vertical members of tubular structures that comprise offshore platforms. Occasionally, UWHs are built to stand on the seafloor with hydraulically adjustable legs to allow them to sit over a pipe.

Divers can work in the dry environment of a UWH for several hours at a time and complete welds of a quality comparable to that achieved on land. This is possible because of good illumination, the divers are not preoccupied with keeping warm, welding surfaces are dry, and inspection and monitoring of the work can be done easily compared to wet welding. Combined with saturation diving or when evacuated to 1 atmosphere, the UWH has been a highly successful tool for offshore pipeline and structural repairs for the past 15 years to depths up to 1000 feet (304.9 m) (Delaune, 1979).

Although at present almost all underwater welding is performed manually, efforts are underway to develop "smart" welding machines incorporating real-time remote sensing and control systems (Masubuchi, Gaudiano, and Reynolds, 1983). Such systems ultimately may replace the underwater welder in the same way that human welders are now being replaced in land-based factories.

Underwater welding habitats also are being developed in the Soviet

Union. Figure 9-32 depicts the PRK-1 UWH, a model of which is on permanent display at the Science and Technology Fair in Moscow (Anon., 1978). While the basic approach is the same, the PRK-1 has a separate lock-in and control chamber and has large, open ballast trays. Information indicates that this system may not be operational yet.

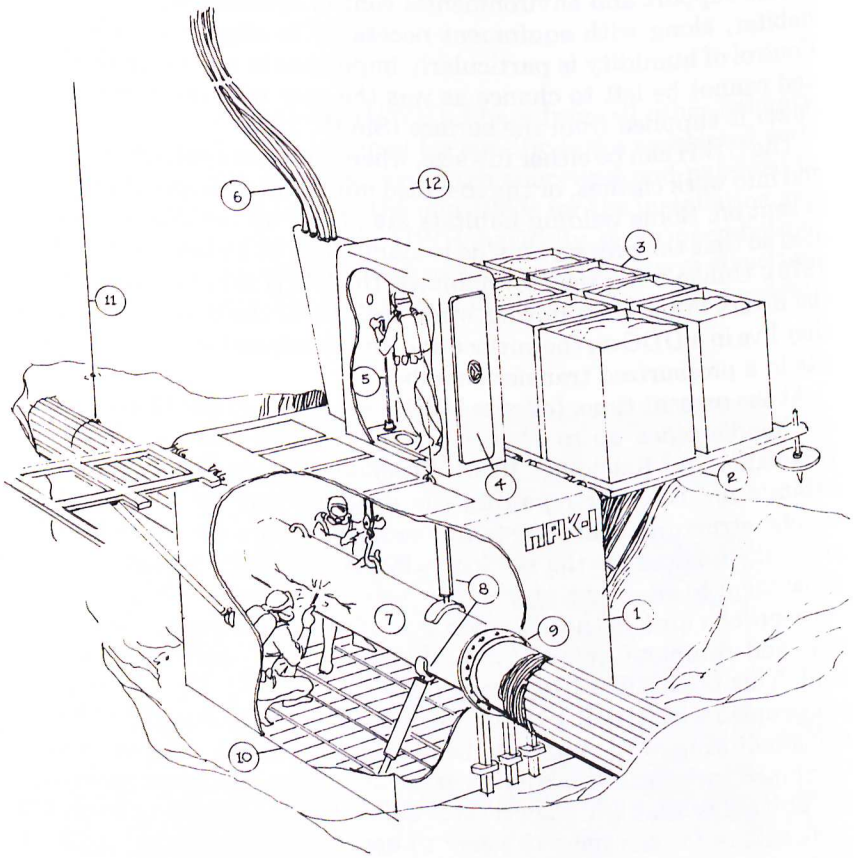


Figure 9-32. Soviet underwater welding habitat PRK-1. *(After Anonymous, 1978), Underwater Repair, Nauka i zhizn', No. 5, insert vi-vii.)*
1. Chamber hull 2. Fold-down rack for ballast boxes 3. Removable boxes with silt ballast 4. Lock for entering chamber 5. Chamber water blowing and flooding system 6. Cables and hoses for telephone communication, power, lights, welding power, hydraulic oil for drives, and air for blowing the chamber and operating the sealing systems 7. Damaged pipe 8. Hydraulic centering device 9. Watertight seal around pipe 10. Liftable floor gratings 11. Marker buoy line 12. Guideline for divers

XENIE-I

Czechoslovakia, 1967

An underwater tent designed by Prague engineer Pavel Gross was tested in the summer of 1967 in Adriatic waters off the Yugoslav city of Portoroze. The aquanaut, Jezisek, spent 3 days in the self-supporting tent at a depth of 19.7 feet (6 m). The tent was 6.6 feet (2 m) long, 3.3 feet (1 m) wide, and 3.3 feet (1 m) high. It weighed 264 pounds (120 kg) and had a displacement of 1.2 tons. Air was provided by two compressors (one reserve), and diving equipment was available for excursions into the water or for emergencies. The tent contained a lighting system and a telephone link to shore. Diver pulse and other vital functions were monitored by remote control. Food was delivered by surface-support personnel.

A larger two-man tent (Xenie-II) was to have been constructed to operate at depths up to 65 feet (19.8 m), but it never came to fruition. No further description of this program is available.

NAME	COUNTRY	DATE	LOCATION	DEPTH (m)	CREW	DURATION (DAYS)	SIZE (m)	WEIGHT (TONS)	HABITAT GAS	SURFACE SUPPORT	MOBILITY	DECOMP. (HOURS)	REMARKS
Xenie	Czech	1967	Adriatic	6	1	3	L=3.3 H=1.0 W=1.0	0.13	Air	Shore	Readily movable	-	-

MANAGEMENT OF HABITAT PROGRAMS

The development, implementation, and management of the habitat programs described in the preceding pages resulted usually from the efforts of a few dedicated individuals. In some programs, such as Hydrolab and La Chalupa, the number of participants remained small; in others, including Tektite and Chernomor, the support team swelled to over 100. Regardless of the size of the program, certain key functions must be satisfied if the project is to be carried out effectively and safely. Because there are numerous sources available describing general management practices, only functions relating directly to habitat programs will be addressed.

Future habitat programs probably will not be conducted on a scale comparable to large programs of the past because of cost, logistics, and other factors discussed in Chapter 10. For these reasons, the La Chalupa program has been selected as a guideline for the operational management of future habitats. La Chalupa required a relatively small surface-support team, was a scientifically oriented program, and came late in the 21-year

ession of habitats; thus its design and management practices bene-
from the programs that preceded it.

ne management of habitat programs basically is no different from the
agement of other endeavors. It begins with the identification of a set
als, which in turn establishes the design of the habitat, the selection
site, and the development of general operational procedures. For
nple, the La Chalupa habitat (Fig. 4-41) was constructed to permit
cquisition of marine scientific data in the waters surrounding Puerto
. Because data were required from several locations, the need for
ility dictated the overall concept of the habitat.

rom the beginning, the La Chalupa program was under the complete
rol of the program manager. The design of the habitat and its mode of
ation required a relatively small support team that was selected
fully to ensure backgrounds compatible with the job requirements.
h team member was trained thoroughly; those whose performance
unsatisfactory were dismissed. As habitat program goals and design
epts are developed, it is essential that the preparation of a program
n and operation manuals begin. This procedure will uncover
inistrative, technical, safety, and programmatic problems that can
emedied during early stages of planning and/or construction if the
gram involves building a new habitat. An important part of planning
his early stage is playing the what-if game. What if bad weather is
ountered? What if spare parts are unavailable? The results of the
t-if game should be used to establish design and operational criteria
safety practices.

he organization of the La Chalupa program is shown in Figure 9-33
ch identifies eight principal functions. Although more than one func-
n may be filled by the same person or a part-time individual, the duties
ntified are necessary to ensure a successful and safe program. In
lition to the functions shown, individuals must be identified to serve
watch officers and safety divers. The former report to the on-site
ector and are responsible for monitoring the surface-based command
l control center. The safety divers report to the dive director and are
ponsible for supporting and resupplying the aquanauts, responding to
ergencies, and assisting the science program director. A habitat engi-
r who is a member of the aquanaut team also should be designated.
s or her primary responsibility is to operate and maintain the habitat,
h a secondary duty of supporting the science program. The habitat
gineer reports regularly to the dive director on the status of the habitat.
is arrangement significantly reduces the need for the aquanaut scien-
t to spend time performing maintenance and repair tasks. A detailed
scription of the duties of each member of the support team should be
luded in the operations manual.

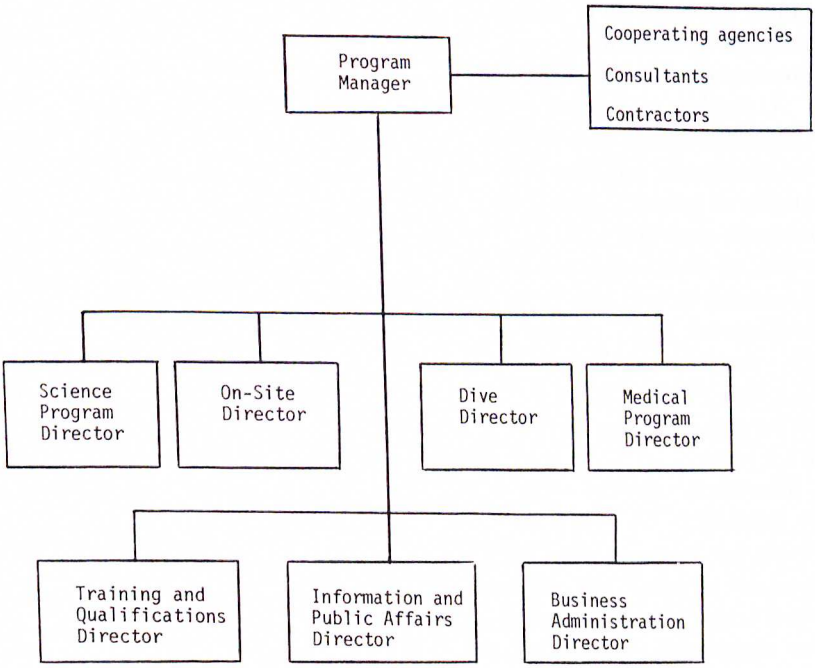


Figure 9-33. Organization of La Chalupa habitat program.

In addition to identifying the key personnel and their responsibilities, it is essential to prescribe guidelines and rules for daily operations. The mission of many programs has suffered for the lack of such mundane things as a shear pin for an outboard motor, a malfunctioning carburetor in the only jeep on shore, or a defective refrigerator or freezer used for the storage of food and specimens. The tight control of maintenance, vehicles, boats, and diving equipment is sometimes as important as the selection of the individual aquanauts. For example, support boats that operate perfectly when used by one person may quickly become useless when operated by another unless strict checklists and procedures are followed. During the La Chalupa program, all boats had radios used by support personnel to report each trip to the watch officer. Such attention to detail pays off with respect to maintenance, fuel consumption, and availability of boats for use in the event of an emergency.

The aquanaut teams for the La Chalupa program were comprised of scientists with previous saturation diving experience ranging from zero to the scientist with the most habitat experience in the world. With respect to conventional diving, the experience ranged from 10 to 3000

hours. An analysis of aquanaut dive times while living in La Chalupa revealed no significant correlation between an aquanaut's estimate of previous dive time and the time spent in the water during a mission.

A number of factors account for this lack of correlation. The La Chalupa program was committed to making saturation diving available to the scientific community in general so as to obtain the highest possible quality of scientific data. Aquanauts thus were selected based on their scientific credentials rather than on diving skills. If there was evidence of a lack of diving skills on the part of the aquanauts, the mission was structured to take this into account without hampering the output or endangering the participants. Another factor affecting aquanaut dive time was that experienced aquanauts learned to substitute good planning for excessive dive time. Thus, scientists with previous saturation diving experience did not tend to lead their missions with respect to time in the water.

The first few days of a mission usually are very active but not necessarily productive. Time is spent in habitat repairs, getting organized, or simply not knowing what to do. Data collected during 11 La Chalupa missions revealed that the amount of work accomplished during the initial 4 days of acclimatization is independent of previous habitat saturation experience. Another interesting feature of habitat life is that in addition to such factors as fatigue, psychological letdown, and equipment failures, there seems to be a mid-mission reduction in dive time. This phenomenon may be related to motivation, length of mission, crew composition, or any number of other factors. Based on the La Chalupa data, conversations with numerous aquanauts, and personal experience, it appears that the optimum mission duration for currently available seafloor habitats is 10 to 21 days, with an optimum time of about 16 days. The 4- or 5-day mission is too short to get over the acclimatization period, and missions exceeding 3 weeks begin to be physically and psychologically fatiguing for both the aquanauts and the surface-support team. Without doubt, improved habitats plus the use of autonomous or shore-based systems can significantly increase both the productivity and optimum length of seafloor missions.

SUMMARY

Our review of undersea habitats has revealed the determination and dedication of divers, explorers, and adventurers to learn more of the sea and how to become part of it. As a result of their efforts, 65 habitats were built between the years 1962 and 1977 (Fig. 9-34), plus numerous under-

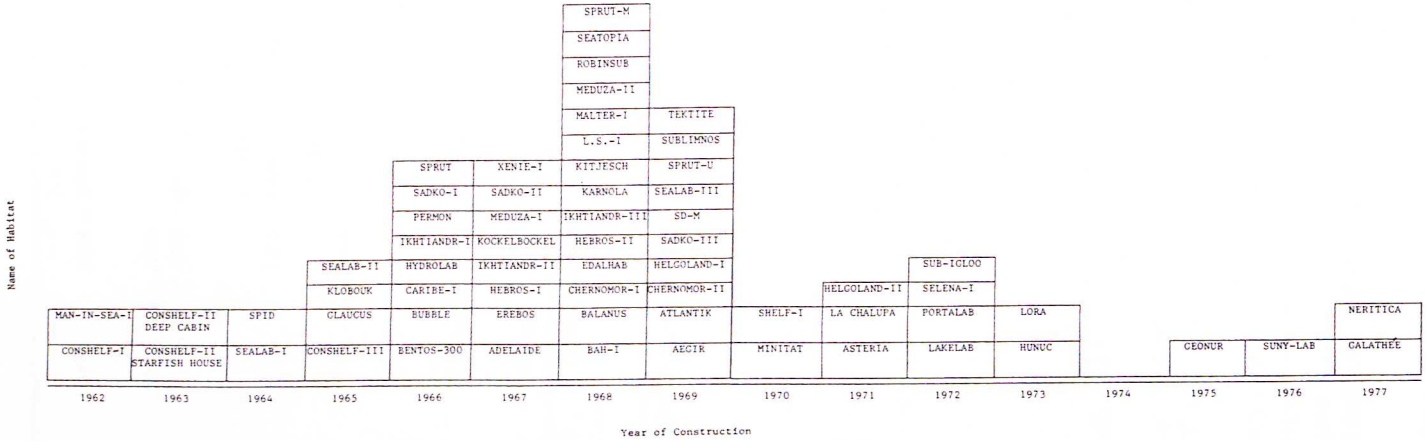


Figure 9-34. Chronology of construction of undersea habitats.

Habitats Around the World

National Origin of Undersea Habitats

ountry	*Number of Habitats*
ıstralia	1
lgaria	3
nada	3
echoslovakia	6
deral Republic of Germany	3
ance	5
erman Democratic Republic	1
eat Britain	3
olland	1
ael	1
aly	3
pan	1
land	3
mania	1
uth Africa	1
viet Union	15
ited States	14
tal	65

mmary of Specifications and Operational Data of Undersea Habitats

Name	*Country*	*Date*	*Location*	*Depth (m)*	*Crew*	*Duration (Days)*
Adelaide	Australia	1967-1968				14+
Aegir	U.S.A.	1969-1971	Hawaii	24-157	4-6	14
Asteria	Italy	1971	Lake Garda	50		
Atlantik	Italy	1969	Lake Cavazzo	12	4	
BAH-I	Federal Republic of Germany	1968-1969	Baltic	10	2	11
Balanus	USSR	1968	Japanese Sea	5		

water welding habitats. These 65 habitats represent separate structures or an extensive modification of a previous habitat, such as was the case in converting Sealab II to Sealab III. The same habitat used for multiple missions such as Tektite I and II or those with minor changes are not counted as separate habitats.

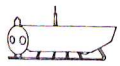
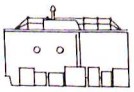
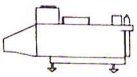
As Table 9-3 shows, habitats were constructed in 17 countries. To the best of our knowledge, the last habitats built were Neritica in Israel and Galathee in France in 1977. Although the Malter-I habitat in East Germany and the LS-I in Rumania possibly are being used for occasional projects and training respectively, the only habitat currently being used regularly for seafloor scientific programs is Hydrolab in the U.S. Virgin Islands.

Table 9-4 summarizes some of the specifications and operational data of all known habitats. A glance at this table causes one to reflect as to why there is only one habitat now in service in an age where there is such worldwide concern for the well-being of our environment and the development of the vast resources of the oceans.

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
			Ship raft			From pontoons
2 cyl., 2.7 × 4.6 plus 3m sphere	200	N_2/O_2 He/O_2	Ship	Towable		Can ascend and descend by interna control
		Air He/O_2				Diver training, instrument testing
L=7 W=2	44 Displ. Each	Air	Shore			3 separate habitat Primary compresso located on seaflo
L=6 D=2	20	N_2/O_2	Ship	Readily movable		
H=5.5 D=1.2	5	Air	Shore			Observation chamber

(continued

Table 9-4. *(continued)*

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)
	Bentos-300	USSR	1966	Sevastopol	300	24	14
	Bubble	U.K.	1966	Malta	10	2-3	1
	Caribe-I	Cuba-Czech	1966	Rincon de Guanabo near Havana	20	2	3
	Chernomor-I	USSR	1968	Black Sea	5-14	4-5	4-6
	Chernomor-II	USSR	1969-1974	Black Sea	5-31	4-5	14-52
	Conshelf-I Diogenes	France	1962	Marseilles, Mediterranean Sea	10	2	7
	Conshelf-II Starfish House	France	1963	Shaab Rumi Reef, Red Sea	11	5	30
	Conshelf-II Deep Cabin	France	1963	Shaab Rumi Reef, Red Sea	27.4	2	7
	Conshelf-III	France	1965	Mediterranean Sea	100	6	22
	Edalhab	U.S.A.	1968 1972	Alton's Bay, N.H.; Miami, Fla.	12.2 13.7	3	3-5
	Erebos	Czech	1967-1968	Olsany	11.5	2	
	Galathee	France	1977		Approx. 18	5	2
	Geonur	Poland	1975-1976	Gdynia	50	4	

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
L=21 W=5.5 H=11.2	500	Air He/O_2	Ship buoy	Self-propelled		Only self-propelled habitat
D=2.1 Sphere	8 Bal.	Air	Shore	Readily movable	0	Decompression experiments
L=3.5 D=1.5	6 Bal.	Air	Ship	Readily movable		First Eastern Bloc habitat
L=7.9 D=2.9	62 Displ.	Air	Ship	Towable		
L=8 D=3	74 Displ.	Air N_2/O_2	Ship	Towable	Varied	Modified Chernomor-I
L=5.2 D=2.4		Air	Ship Shore	Readily movable	3	
10.4 4 legs 1.2×2.4	100 Bal.	Air	Ship	Readily movable	2.5	
D=2.0		50% He 50% Air	Ship	Towable	3.5 from 27.4 m to 11 m	
D=5.5 sphere	130+	2.5% O_2 97.5% He	Ship	Towable	84	Mounted on 8.5 × 14.6 m barge
L=3.6 D=2.4	14 25	Air	Shore ship	Readily movable	19	
L=2.7 W=1.3 H=1.8	15 Bal.	Air	Shore	Readily movable		Deployed in quarry
L=7 W=6.6 H=4.8	7	Air	Ship			
H=7.6 W=4.2	34		Ship	Towable		For geology

(continued)

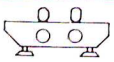
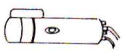
. *(continued)*

	Name	*Country*	*Date*	*Location*	*Depth (m)*	*Crew*	*Duration (Days)*
	Glaucus	U.K.	1965	Plymouth	10.7	2	7
	Hebros-I (Khebros)	Bulgaria	1967	Lake Varna	7	2	7
	Hebros-II	Bulgaria	1968		30		10
	Helgoland-I	Federal Republic of Germany	1969	North Sea	23	2-4	5-11
	Helgoland-II	Federal Republic of Germany	1971 1977	North Sea Baltic, USA	22-31	4	4-14
	HUNUC	South Africa	1972	Durban	10	4	N/A
	Hydrolab	U.S.A.	66-70 70-74 75-84	Florida Bahamas Virgin Islands	12-18	2-4	7-14
	Ikhtiandr	USSR	1966	Crimean Coast Black Sea	12	3	7
	Ikhtiandr	USSR	1967	Crimean Coast Black Sea	12.2	2-5	7
	Ikhtiandr	USSR	1968	Crimean Coast Black Sea	10	4	3
	Karnola	Czech	1968		8 15	5	3-7
	Kitjesch (Kitezh)	USSR	1965	Crimean Coast	15	4	
	Klobouk (Hat)	Czech	1965	Koza-rovice	6	4	Daily visits
	Kockelbockel	Netherlands	1967	Sloterplas	15	2-4	Short period

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
W=2.1 L=3.6	13	Air	Shore	Readily movable	3.0-3.5	Decompression experiments
L=5.5 D=2.0		Air	Shore	Towable		Made from a locomotive boiler
W=2.5 L=6.7			Shore			Not known if used
L=9.0 D=6.0	75	N_2/O_2	Buoy	Readily movable	Varied	
L=13.8 W=6.0	102	N_2/O_2	Buoy	Towable	Varied	Modified Helgoland-I
L=5.9 W=1.5		Air	Shore	Movable		Sank during emplacement—never occupied
L=4.9 W=2.4	40	Air	Buoy	Towable	13-20	Most utilized habitat in the world
L=2.2 W=1.6 H=2.0	10 Bal.	Air	Shore	Readily movable		
3 cubes L=8.6 H=7.0		Air	Shore	Readily movable		2 female aquanauts
		Air	Shore	Readily towable		
H=7.0				Readily movable		
L=6.3 W=2.2	25		Shore			Made from a converted railroad tankcar
L=1.2 H=1.0		Air	Shore	Readily movable		
D=1.9 H=4.6	9.5+	Air	Autonomous	Readily movable		

(continued)

Table 9-4. *(continued)*

	Name	*Country*	*Date*	*Location*	*Depth (m)*	*Crew*	*Duration (Days)*
	La Chalupa	U.S.A.	1971–1974	Puerto Rico	15–30	4–5	14
	Lakelab	U.S.A.	1972	Grand Traverse Bay, Michigan	15.2	2	2
	LORA	Canada	1973–1975	New-foundland	7.9	2	1
	LS-I	Rumania	1967	Lake Bicaz	12–14	3–4	30
	Malter-I	German Democratic Republic	1968–1983	Malter Dam	8	2–4	2–7
	Man-in-Sea I	U.S.A.	1962	Mediterra-nean	61	1	1
	Meduza-I	Poland	1967	Lake Klodno	24	2	4
	Meduza-II	Poland	1968	Gdansk, Baltic Sea	26	3	7
	Minitat	U.S.A.	1970	Virgin Islands	30.5	2	14
	Neritica	Federal Republic of Germany/ Israel	1977	Eilat, Red Sea	9	2–3	16
	Permon-II/III	Czech	1966 1967	Bruntanya	10	2	3
	Portalab	U.S.A.	1972	Rhode Island	11.3	2	<1
	Robinsub-I	Italy	1968	Ustica Island	10	1	2

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
2 cyl. 2.4×6.0 1 rm 3×6	150	N_2/O_2	Buoy	Readily movable	36-48	Farthest operation from shore
D=3.0 H=2.1	24 Bal.	Air	Shore	Readily movable	N/A	
L=2.4 D=4.9	24 Bal.	Air	Shore	Fixed	0	Under ice
L=7.2 D=2.4	20 Bal.	Air	Ship	Readily movable	48	Still used for observation
L=4.2 D=2.0	14	Air	Shore	Readily movable		Under ice
L=3.2 D=0.9	2.1 incl Bal.	3% O_2 97% He	Ship	Readily movable	65.5	World's first open sea saturation
L=2.2 W=1.8 H=2.1	3.0	37% O_2 63% N_2	Shore	Readily movable	53.5	Entire habitat raised for decompression
L=3.6 W=2.2 H=1.8	8	Air	Ship	Readily movable	22	Excursions to 50m
H=3.4 D=2.4	13.5 displ.	N_2/O_2	Ship	Towable	N/A	Never operational
L=3.4 W=2.0	3	Air	Shore	Readily movable	14	
L=2.0 W=2.0		N_2/O_2	Shore	Readily movable		
L=2.4 W=1.8 H=2.1	7.2 Bal.	Air	Shore	Readily movable	0	
L=2.5 W=1.5 H=2.0	7.5 Displ.	Air	Shore	Readily movable		Wire cage/ plastic tent

(continued)

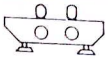
e 9-4. *(continued)*

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)	Size (m)	Weight (Tons)
	La Chalupa	U.S.A.	1971–1974	Puerto Rico	15–30	4–5	14	2 cyl. 2.4×6.0 1 rm 3×6	150
	Lakelab	U.S.A.	1972	Grand Traverse Bay, Michigan	15.2	2	2	D=3.0 H=2.1	24 Bal.
	LORA	Canada	1973–1975	New-foundland	7.9	2	1	L=2.4 D=4.9	24 Bal.
	LS-I	Rumania	1967	Lake Bicaz	12–14	3–4	30	L=7.2 D=2.4	20 Bal.
	Malter-I	German Democratic Republic	1968–1983	Malter Dam	8	2–4	2–7	L=4.2 D=2.0	14
	Man-in-Sea I	U.S.A.	1962	Mediterra-nean	61	1	1	L=3.2 D=0.9	2.1 in Bal.
	Meduza-I	Poland	1967	Lake Klodno	24	2	4	L=2.2 W=1.8 H=2.1	3.0
	Meduza-II	Poland	1968	Gdansk, Baltic Sea	26	3	7	L=3.6 W=2.2 H=1.8	8
	Minitat	U.S.A.	1970	Virgin Islands	30.5	2	14	H=3.4 D=2.4	13. disp
	Neritica	Federal Republic of Germany/ Israel	1977	Eilat, Red Sea	9	2–3	16	L=3.4 W=2.0	3
	Permon-II/III	Czech	1966 1967	Bruntanya	10	2	3	L=2.0 W=2.0	
	Portalab	U.S.A.	1972	Rhode Island	11.3	2	<1	L=2.4 W=1.8 H=2.1	7 B
	Robinsub-I	Italy	1968	Ustica Island	10	1	2	L=2.5 W=1.5 H=2.0	7 Di

	Habitat Gas	Surface Support	Mobility	Decompression (Hours)	Remarks
	N_2/O_2	Buoy	Readily movable	36–48	Farthest operation from shore
	Air	Shore	Readily movable	N/A	
	Air	Shore	Fixed	0	Under ice
	Air	Ship	Readily movable	48	Still used for observation
	Air	Shore	Readily movable		Under ice
cl	3% O_2 97% He	Ship	Readily movable	65.5	World's first open sea saturation
	37% O_2 63% N_2	Shore	Readily movable	53.5	Entire habitat raised for decompression
	Air	Ship	Readily movable	22	Excursions to 50m
5 pl.	N_2/O_2	Ship	Towable	N/A	Never operational
	Air	Shore	Readily movable	14	
	N_2/O_2	Shore	Readily movable		
.2 al.	Air	Shore	Readily movable	0	
.5 spl.	Air	Shore	Readily movable		Wire cage/ plastic tent

(continued)

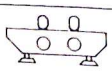
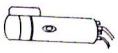
Table 9-4. *(continued)*

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)
	La Chalupa	U.S.A.	1971–1974	Puerto Rico	15–30	4–5	14
	Lakelab	U.S.A.	1972	Grand Traverse Bay, Michigan	15.2	2	2
	LORA	Canada	1973–1975	Newfoundland	7.9	2	1
	LS-I	Rumania	1967	Lake Bicaz	12–14	3–4	30
	Malter-I	German Democratic Republic	1968–1983	Malter Dam	8	2–4	2–7
	Man-in-Sea I	U.S.A.	1962	Mediterranean	61	1	1
	Meduza-I	Poland	1967	Lake Klodno	24	2	4
	Meduza-II	Poland	1968	Gdansk, Baltic Sea	26	3	7
	Minitat	U.S.A.	1970	Virgin Islands	30.5	2	14
	Neritica	Federal Republic of Germany/ Israel	1977	Eilat, Red Sea	9	2–3	16
	Permon-II/III	Czech	1966 1967	Bruntanya	10	2	3
	Portalab	U.S.A.	1972	Rhode Island	11.3	2	<1
	Robinsub-I	Italy	1968	Ustica Island	10	1	2

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
2 cyl. 2.4×6.0 1 rm 3×6	150	N_2/O_2	Buoy	Readily movable	36-48	Farthest operation from shore
D=3.0 H=2.1	24 Bal.	Air	Shore	Readily movable	N/A	
L=2.4 D=4.9	24 Bal.	Air	Shore	Fixed	0	Under ice
L=7.2 D=2.4	20 Bal.	Air	Ship	Readily movable	48	Still used for observation
L=4.2 D=2.0	14	Air	Shore	Readily movable		Under ice
L=3.2 D=0.9	2.1 incl Bal.	3% O_2 97% He	Ship	Readily movable	65.5	World's first open sea saturation
L=2.2 W=1.8 H=2.1	3.0	37% O_2 63% N_2	Shore	Readily movable	53.5	Entire habitat raised for decompression
L=3.6 W=2.2 H=1.8	8	Air	Ship	Readily movable	22	Excursions to 50m
H=3.4 D=2.4	13.5 displ.	N_2/O_2	Ship	Towable	N/A	Never operational
L=3.4 W=2.0	3	Air	Shore	Readily movable	14	
L=2.0 W=2.0		N_2/O_2	Shore	Readily movable		
L=2.4 W=1.8 H=2.1	7.2 Bal.	Air	Shore	Readily movable	0	
L=2.5 W=1.5 H=2.0	7.5 Displ.	Air	Shore	Readily movable		Wire cage/ plastic tent

(continued)

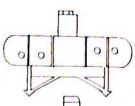
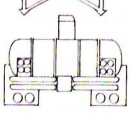
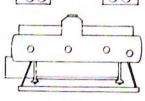
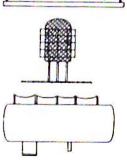
Table 9-4. *(continued)*

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)
	La Chalupa	U.S.A.	1971–1974	Puerto Rico	15–30	4–5	14
	Lakelab	U.S.A.	1972	Grand Traverse Bay, Michigan	15.2	2	2
	LORA	Canada	1973–1975	New-foundland	7.9	2	1
	LS-I	Rumania	1967	Lake Bicaz	12–14	3–4	30
	Malter-I	German Democratic Republic	1968–1983	Malter Dam	8	2–4	2–7
	Man-in-Sea I	U.S.A.	1962	Mediterra-nean	61	1	1
	Meduza-I	Poland	1967	Lake Klodno	24	2	4
	Meduza-II	Poland	1968	Gdansk, Baltic Sea	26	3	7
	Minitat	U.S.A.	1970	Virgin Islands	30.5	2	14
	Neritica	Federal Republic of Germany/ Israel	1977	Eilat, Red Sea	9	2–3	16
	Permon-II/III	Czech	1966 1967	Bruntanya	10	2	3
	Portalab	U.S.A.	1972	Rhode Island	11.3	2	<1
	Robinsub-I	Italy	1968	Ustica Island	10	1	2

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
2 cyl. 2.4×6.0 1 rm 3×6	150	N_2/O_2	Buoy	Readily movable	36-48	Farthest operation from shore
D=3.0 H=2.1	24 Bal.	Air	Shore	Readily movable	N/A	
L=2.4 D=4.9	24 Bal.	Air	Shore	Fixed	0	Under ice
L=7.2 D=2.4	20 Bal.	Air	Ship	Readily movable	48	Still used for observation
L=4.2 D=2.0	14	Air	Shore	Readily movable		Under ice
L=3.2 D=0.9	2.1 incl Bal.	3% O_2 97% He	Ship	Readily movable	65.5	World's first open sea saturation
L=2.2 W=1.8 H=2.1	3.0	37% O_2 63% N_2	Shore	Readily movable	53.5	Entire habitat raised for decompression
L=3.6 W=2.2 H=1.8	8	Air	Ship	Readily movable	22	Excursions to 50m
H=3.4 D=2.4	13.5 displ.	N_2/O_2	Ship	Towable	N/A	Never operational
L=3.4 W=2.0	3	Air	Shore	Readily movable	14	
L=2.0 W=2.0		N_2/O_2	Shore	Readily movable		
L=2.4 W=1.8 H=2.1	7.2 Bal.	Air	Shore	Readily movable	0	
L=2.5 W=1.5 H=2.0	7.5 Displ.	Air	Shore	Readily movable		Wire cage/ plastic tent

(continued)

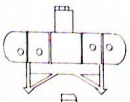
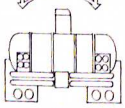
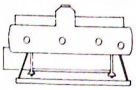
Table 9-4. *(continued)*

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)
	Sadko-I	USSR	1966	Black Sea, Sukumi Bay	12	2	6 hrs/ team
	Sadko-II	USSR	1967	Black Sea, Sukumi Bay	25	2	6
	Sadko-III	USSR	1969	Black Sea, Sukumi Bay	25	3	14
	SD-M	UK	1969	Malta	6–9	2	1–7
	Sealab-I	U.S.A. (Navy)	1964	Argus Island Bermuda	58.8	4	11
	Sealab-II	U.S.A. (Navy)	1965	La Jolla, California	62.5	10	15–30
	Sealab-III	U.S.A. (Navy)	1969	San Clemente, California	182.9	5–12	N/A
	Seatopia	Japan	1968–1973	Yokosuka	30	4	2
	Selena-I	USSR	1972	Beloye Lake	11.5	1	15 hrs.
	Shelf-I	Bulgaria	1970	Burgas Gulf	20	3	4–5
	SPID (Man-in-Sea II)	U.S.A.	1964 1974	Bahamas Canadian Arctic	131.7 4.3	2	1
	Sprut (Octopus)	USSR	1966	Black Sea	10.5	3	14
	Sprut-M	USSR	1968	Black Sea	14	2	
	Sprut-U	USSR	1969–1970	Black Sea	12–34	1–4	

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decom-pression (Hours)*	*Remarks*
D=3 sphere	13.5	Air	Ship shore	Readily movable		Stationed in midwater
D=3 2 spheres	28.5 Bal.	N_2/O_2	Ship shore	Readily movable	70	Stationed in midwater
D=3.0 H=15.0	30 Bal.	He/N_2/ $O/_2$	Ship	Readily movable		Stationed in midwater
L=2.9 W=1.8 H=1.8		Air	Auton-omous			Rubber tent with steel frame
L=12.2 D=2.7 H=4.5	20 Bal.	4% O_2 17%N_2 79% He	Ship	Movable	56	
L=17.5 D=3.6 H=3.6	200	4% O 25% N_2 71% He	Ship	Movable	30	
L=17.5 D=3.6 H=3.6		2% O_2 6% N_2 92% He	Ship	Movable	N/A	Death of aquanaut caused cancellation
L=10.5 W=2.3 H=6.5	65	4.8% O_2 16.0% N_2 79.2% He	Ship	Movable	66	Only used for one open-sea mission
D=2.0 H=3.0	5	Air		Readily movable		Semipermeable membrane
L=6.0 D=2.5	30	Air	Ship	Readily movable	33.5	
L=2.4 W=1.2		3.6% O_2 5.6% N_2 90.8% He	Ship shore	Readily movable	92 0	Inflatable habitat
D=5.0 sphere		Air	Shore	Readily movable		Inflatable habitat
D=2.4		Air	Shore	Readily movable		Inflatable habitat
		Air	Shore	Readily movable		Inflatable habitat

(continued)

Table 9-4. *(continued)*

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)
	Sadko-I	USSR	1966	Black Sea, Sukumi Bay	12	2	6 hrs/ team
	Sadko-II	USSR	1967	Black Sea, Sukumi Bay	25	2	6
	Sadko-III	USSR	1969	Black Sea, Sukumi Bay	25	3	14
	SD-M	UK	1969	Malta	6-9	2	1-7
	Sealab-I	U.S.A. (Navy)	1964	Argus Island Bermuda	58.8	4	11
	Sealab-II	U.S.A. (Navy)	1965	La Jolla, California	62.5	10	15-30
	Sealab-III	U.S.A. (Navy)	1969	San Clemente, California	182.9	5-12	N/A
	Seatopia	Japan	1968-1973	Yokosuka	30	4	2
	Selena-I	USSR	1972	Beloye Lake	11.5	1	15 hrs.
	Shelf-I	Bulgaria	1970	Burgas Gulf	20	3	4-5
	SPID (Man-in-Sea II)	U.S.A.	1964 1974	Bahamas Canadian Arctic	131.7 4.3	2	1
	Sprut (Octopus)	USSR	1966	Black Sea	10.5	3	14
	Sprut-M	USSR	1968	Black Sea	14	2	
	Sprut-U	USSR	1969-1970	Black Sea	12-34	1-4	

Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
D=3 sphere	13.5	Air	Ship shore	Readily movable		Stationed in midwater
D=3 2 spheres	28.5 Bal.	N_2/O_2	Ship shore	Readily movable	70	Stationed in midwater
D=3.0 H=15.0	30 Bal.	$He/N_2/O/_2$	Ship	Readily movable		Stationed in midwater
L=2.9 W=1.8 H=1.8		Air	Autonomous			Rubber tent with steel frame
L=12.2 D=2.7 H=4.5	20 Bal.	4% O_2 17%N_2 79% He	Ship	Movable	56	
L=17.5 D=3.6 H=3.6	200	4% O 25% N_2 71% He	Ship	Movable	30	
L=17.5 D=3.6 H=3.6		2% O_2 6% N_2 92% He	Ship	Movable	N/A	Death of aquanaut caused cancellation
L=10.5 W=2.3 H=6.5	65	4.8% O_2 16.0% N_2 79.2% He	Ship	Movable	66	Only used for one open-sea mission
D=2.0 H=3.0	5	Air		Readily movable		Semipermeable membrane
L=6.0 D=2.5	30	Air	Ship	Readily movable	33.5	
L=2.4 W=1.2		3.6% O_2 5.6% N_2 90.8% He	Ship shore	Readily movable	92 0	Inflatable habitat
D=5.0 sphere		Air	Shore	Readily movable		Inflatable habitat
D=2.4		Air	Shore	Readily movable		Inflatable habitat
		Air	Shore	Readily movable		Inflatable habitat

(continued)

Table 9-4. *(continued)*

	Name	Country	Date	Location	Depth (m)	Crew	Duration (Days)
	Sub-Igloo	Canada	1972–1975	Cornwallis Island	12.2	2-4	1
	Sublimnos	Canada	1969–	Georgian Bay, Ontario	10.1	2-4	Up to 24 hrs.
	Suny-lab	U.S.A.	1976–	New York	12.2	2-3	1
	Tektite I-II	U.S.A.	1969–1970	U.S. Virgin Islands	13.1	4-5	6-59
	Xenie	Czech	1967	Adriatic	6	1	3

Note: Bal. = ballast; displ. = displacement.

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Anonymous, 1976*b*, Underwater Base, *Nauka i zhizn'* **1**:40.

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Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
D=2.5 sphere	8 Bal.	Air	Shore	Readily movable	0	Under ice
H=2.7 D=2.4	9	Air	Ship shore	Readily movable		Designed for day-long occupation
1.5	6	Air	Ship	Readily movable		Made from cement mixer
D=3.8 H=5.5	79	92% N_2 8% O_2	Ship shore	Fixed	19.5	World's longest open-sea saturation
L=3.3 H=1.0 W=1.0	0.13	Air	Shore	Readily movable		

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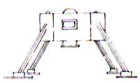	Suny-lab	U.S.A.	1976-	New York	12.2	2-3	1
	Tektite I-II	U.S.A.	1969-1970	U.S. Virgin Islands	13.1	4-5	6-59
	Xenie	Czech	1967	Adriatic	6	1	3

Note: Bal. = ballast; displ. = displacement.

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Size (m)	*Weight (Tons)*	*Habitat Gas*	*Surface Support*	*Mobility*	*Decompression (Hours)*	*Remarks*
D=2.5 sphere	8 Bal.	Air	Shore	Readily movable	0	Under ice
H=2.7 D=2.4	9	Air	Ship shore	Readily movable		Designed for day-long occupation
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Chapter 10

A Look to the Future

Our story of living and working in the sea began over 5000 years ago with the breath-holding pearl divers of the Persian Gulf. While the quest for increased bottom time has taken many forms, it has been only during the last 22 years that humans truly have become part of the undersea world. That aquanauts can live safely and harmoniously in the sea has been demonstrated clearly in the laboratory and in over 60 seafloor habitat programs. How is it, then, that undersea habitats have become almost as extinct as the ancient dodo bird? What went wrong? What happened to the dreams of placing men and women in the sea for weeks or months at a time?

DECLINE OF FIRST GENERATION

Cost-Effectiveness

A major factor leading to the decline of undersea habitats has been cost, or, more precisely, cost-effectiveness. In other words, can the knowledge gained from a seafloor habitat program justify the cost of construction and continued support? An examination of the programs described in the preceding nine chapters reveals that common objectives were to test equipment and to show that humans could work more effectively in the sea if only they could live at the work site. A related secondary go

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and a dream of the earliest seafloor pioneers, was to develop habitats that were independent of the surface which would reduce the costs of support ships and surface crews. The first goal clearly was achieved; the second never has been realized with the exception of the three-day saturation mission in Hydrolab in 1969 during which a fuel cell on the seafloor provided the necessary power. The reliability of operational procedures and support equipment used to date in seafloor programs has been such that abandoning aquanauts to their own devices on the bottom was a risk usually unacceptable to program managers. Thus for reasons of technology, logistics, and safety, independence from the surface has not been accomplished. As a result, costs of supporting a seafloor habitat have gone up instead of down.

An additional cost-related issue is the manner by which habitats have been funded. Whether the program was initiated and carried out by a sport diving club in Eastern Europe, a university in the United States, or a government agency, in most cases a single project was planned, launched, and completed without any assurance or even hope of continued support. This absence of funding continuity created a problem beyond simply the shortage of money. Because of the lack of continuity, many scientists whose programs could have benefited from the use of a habitat did not consider its use because they were unable to count on having one available for any substantial length of time. As a consequence, the use of habitats was not included in scientific proposals, particularly those requiring seasonal data collection over a period of years. The exception was the federally-supported Hydrolab which was operational from 1971-1977 in the Bahamas and from 1978-1985 in the U.S. Virgin Islands. It was installed in the National Museum of Natural History, Wash. D.C. in 1986.

The steady growth of government regulations, the chronic threat of litigation should something go wrong, the increasing costs of insurance, and reluctance to take risks also have contributed to the decline of undersea habitats. The thought of sealing up a molasses barrel, placing it at a depth of 50 feet (15.2 m), and putting divers in it for a few days would scare the legal socks off most organizations.

Lack of Mobility

Another factor limiting the use of habitats has been their lack of mobility. Since they are required to be ballasted heavily, are not designed for towing, and are not self-propelled, a significant effort by surface-support teams has been necessary to move most habitats. As a result, they usually remain at one site for a mission or series of missions, which severely limits the area on the seafloor that can be studied. Historically, the available diving equipment, swimmer propulsion vehicles, and special wet submersibles that can be used safely for extended forays on the surface have not been reliable enough to encourage saturated aquanauts

(Continued from front fl

to venture far from a habitat knowing they could not seek the safety of the surface in the event of an equipment malfunction. This concern is expressed well by Delauze et al. (1977, p.259). "Expensive experiments with electrically propelled tugs and underwater 'chariots' have merely confirmed the suspicion that, although the idea of divers being able to range for miles around a habitat is seductive, the risks of taking saturated men far away from base are too great." The relative immobility of seafloor habitats therefore has required explorers and/or diving scientists to limit their investigations to those that can be carried out within a radius of approximately 1000 feet (305 m) around the habitat. In water with poor visibility, this area is restricted even further.

The problem of limited mobility has been overcome in the field of commercial saturation diving by housing the divers in a DDC located on a surface ship or platform at a pressure approximating that of the working depth on the seafloor. The divers then are transported to the bottom work site under pressure in a PTC. Once on the bottom, the PTC is opened and the divers exit, with life support provided through an umbilical attached to the PTC. When ready to return to the "surface," they again enter the PTC, which then is hauled to the surface and mated to the DDC, with the divers kept continually under pressure (Fig. 10-1).

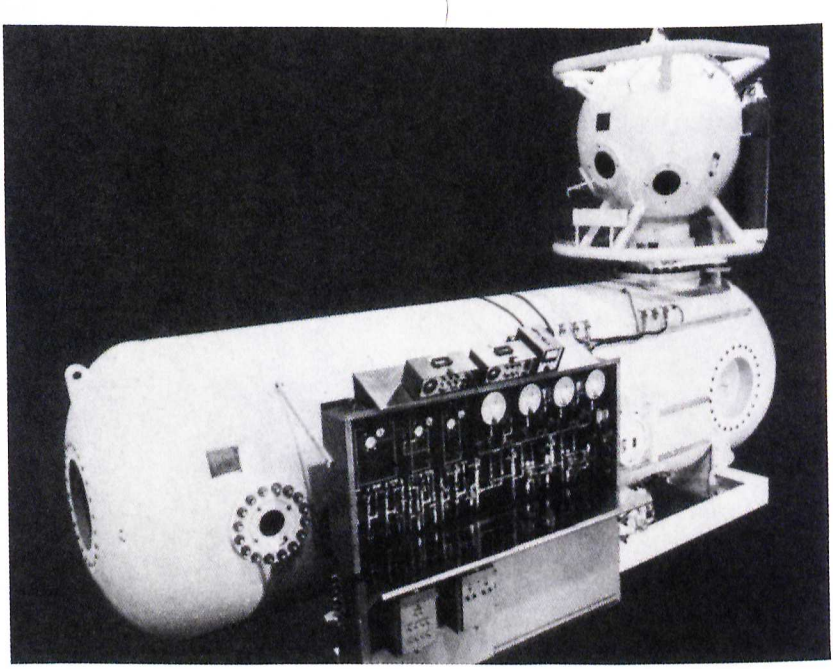


Figure 10-1. Saturation diving system rated for 1500 feet of seawater. *(Courtesy of Perry Oceanographics, Inc., Riviera Beach, Florida.)*

The use of this procedure capitalizes on the advantages of saturation diving and provides the necessary mobility to move the operation from site to site. It also facilitates the support of the divers with respect to supplies, food, medical care, and decompression and permits hasty withdrawal in the event of bad weather. While this system offers many advantages for commercial diving projects, the cost is prohibitive for the low-budgeted scientific undersea program.

In addition to restrictions placed on scientific habitat programs due to lack of mobility, the myriad of equipment problems and discomforts encountered in the past programs frequently has discouraged scientists from participating. In the minds of many, habitats were for the adventuresome diver and explorer rather than for the serious scientist who preferred not to spend large amounts of time simply keeping things going.

New Technology

The use of seafloor habitats also has been affected in the past few years by great advances in science and technology that offer the scientist, explorer, or underwater worker several alternative methods of achieving the same goals. For example, the sophisticated 1 atmosphere submersible vehicles now available, including those that permit divers to exit into the water (Fig. 10-2), have added an entirely new dimension to ocean

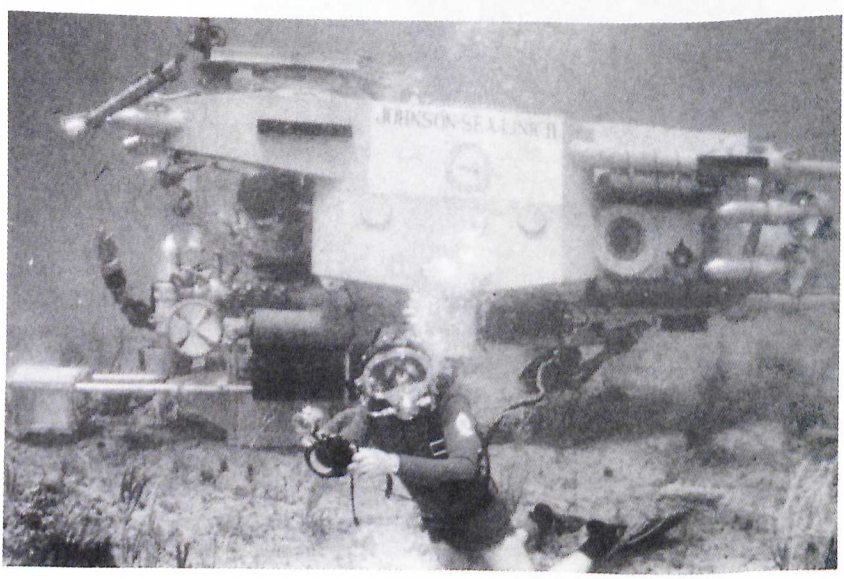


Figure 10-2. Johnson Sea-Link diver lockout submersible. *(Courtesy of Harbor Branch Foundation, Inc., Fort Pierce, Florida.)*

exploration. Other advances in recent years include 1 atmosphere diving suits in which a working diver or scientist can descend to depths of 2000 feet (609.8 m), stay for several hours, return to the surface, and step out immediately with no requirements for decompression. The 1 atmosphere diving system JIM-4 is shown in Figure 10-3 during performance tests at the Naval Medical Research Institute.

Perhaps even more impressive is the remarkable development of remotely operated submersible vehicles (ROVs). There seemingly is an endless variety of combinations of ROVs, which incorporate manipulators, cameras, robots, and vehicles for working and gathering data in the sea. Figure 10-4 shows a self-propelled ROV capable of operating to depths of 1950 feet (600 m), equipped with a television camera, being lowered over the side and deployed under water. These devices, which can come equipped with special sensors such as low-light-level TV systems and servo-controlled depth and heading, can be used for observation, inspection of offshore oil structures, search and salvage, and oceanographic surveys. When coupled with sophisticated data transmission systems and modern com-

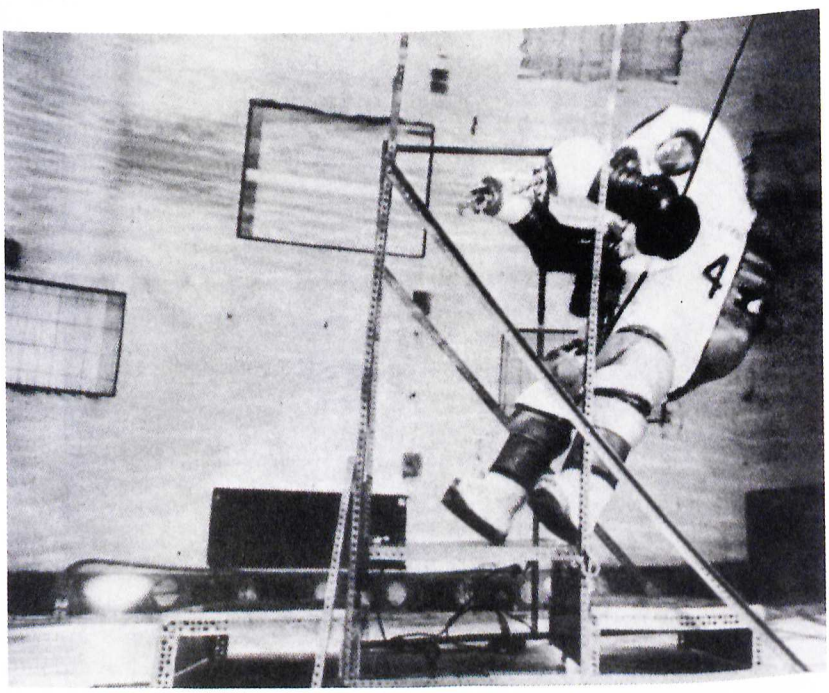
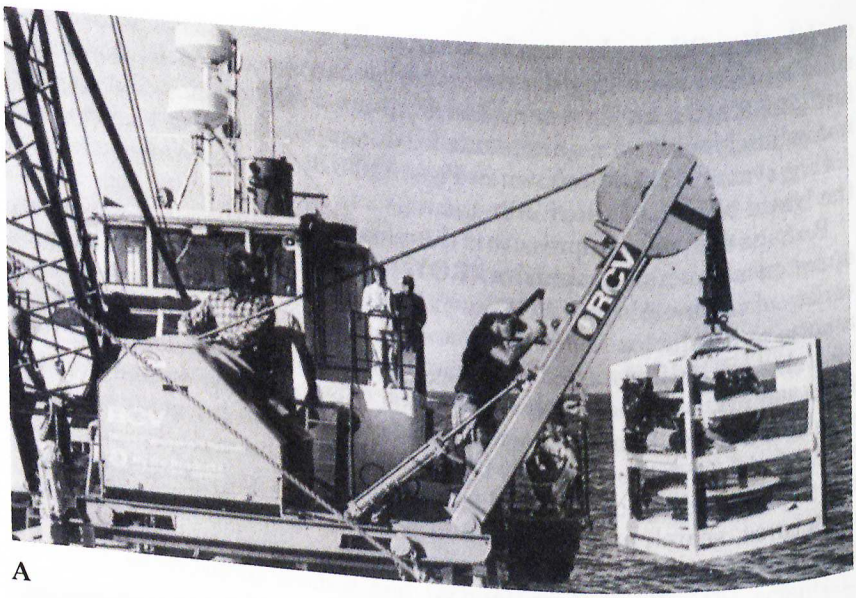


Figure 10-3. One-atmosphere diving system JIM-4. *(From A. Bachrach, 1981, A Biomedical Assessment of a One-Atmosphere Diving System; JIM-4 Final Report, Naval Medical Research Institute Project M00099PN.003.3030, NMRI81-70, Bethesda, Md. By permission.)*



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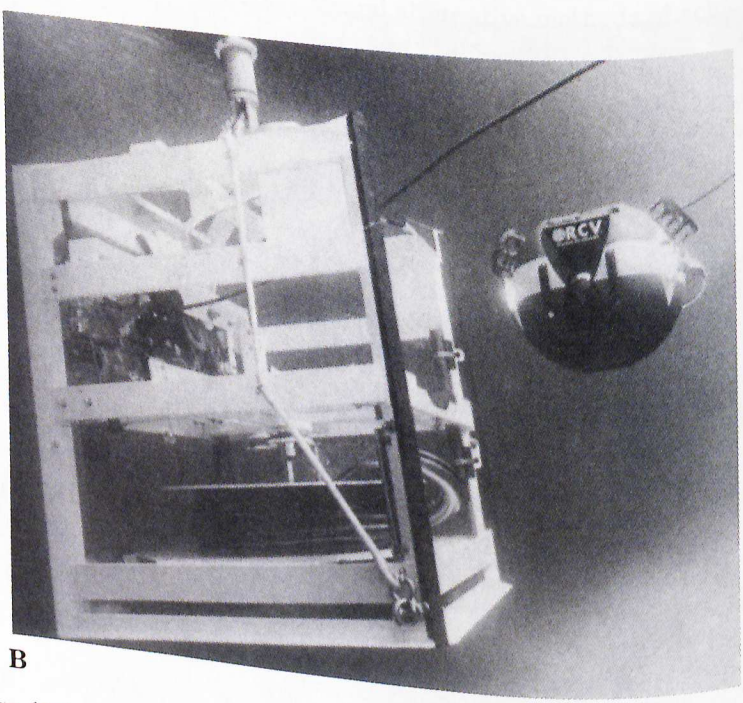


B

Figure 10-4. An advanced remotely operated vehicle system (ROV). *A*: Being lowered over side; *B*: deploying under water. *(Courtesy of Hydro Products, San Diego, California.)*

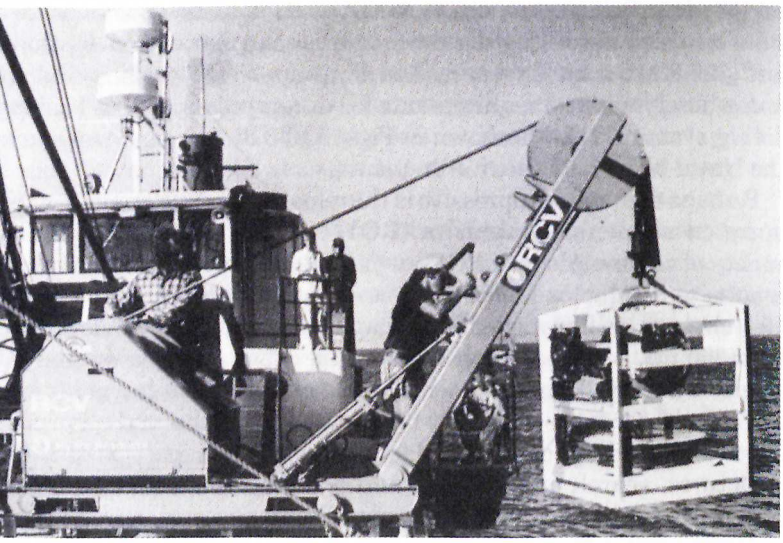
puter facilities via a surface-based control system, these new machines are accomplishing tasks and producing data at an unprecedented rate. Data soon will be transmitted back to the surface over fiber-optic cables so fine that 5 miles of them will fit into a coffee can.

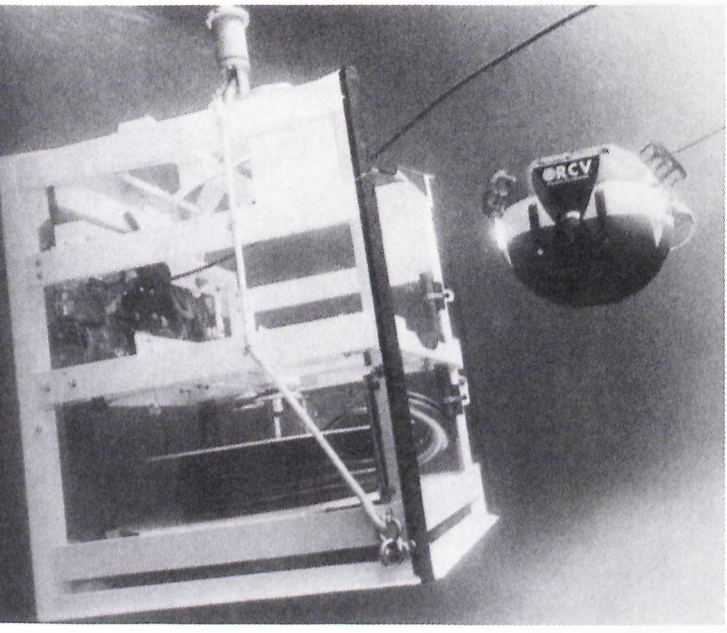
Figurative marriages between humans and machines will become as commonplace in the exploration of the oceans as they now are on land. Such marriages in the past often have been preceded by long and stormy courtships, reluctance to rescind independence, and problems relating to the domination of one species by the other. Many are finding that their roles as humans are shifting systematically from active participant and controller to that of monitoring and supervising machines. This shifting role is described aptly by Issac Asimov in his book *I Robot* (1950, p.52). The context of the following quote is a conversation between a scientist in the year 2057 and a robot who refuses to believe he was constructed by humans whom he regards as inferior. The robot speaks.

> "Look at you," he said finally, "I say this in no spirit of contempt, but look at you. The material you are made of is soft and flabby, lacking endurance and strength, depending for energy upon the inefficient oxidation of organic material-like that." He pointed a disapproving finger at what remained of Donovan's sandwich. Periodically you pass into a coma and the least variation in temperature, air pressure, humidity, or radiation intensity impairs your efficiency. You are makeshift. I, on the other hand, am a finished product. I absorb electrical energy directly and utilize it with an almost one hundred percent efficiency. I am composed of strong metal, am continuously conscious, and can stand extremes of environment easily. These are facts which, with the self-evident proposition that no being can create another being superior to itself, smashes your silly hypothesis to nothing."

NEXT GENERATION

What does the future hold for undersea habitats? Will man's place in the sea as a diver-aquanaut be usurped entirely by machines operated either remotely from the surface, from 1 atmosphere manned submersibles, or with the aid of 1 atmosphere diving systems? If the working depths are beyond about 300 feet (91.5 m), the answer probably is yes. With new machines providing engineering solutions to medical problems, the high cost of constructing and supporting deep diving saturation systems, including long and costly decompressions amounting to a little less than 1 day per 100 feet (30.5 m) of saturation depth, are making them noncompetitive with unmanned systems. Although there will continue to be a requirement for the specialized deep diver for a while, we believe that





10-4. An advanced remotely operated vehicle system (ROV). *A*: Being d over side; *B*: deploying under water. *(Courtesy of Hydro Products, San California.)*

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puter facilities via a surface-based control system, these new machines are accomplishing tasks and producing data at an unprecedented rate. Data soon will be transmitted back to the surface over fiber-optic cables so fine that 5 miles of them will fit into a coffee can.

Figurative marriages between humans and machines will become as commonplace in the exploration of the oceans as they now are on land. Such marriages in the past often have been preceded by long and stormy courtships, reluctance to rescind independence, and problems relating to the domination of one species by the other. Many are finding that their roles as humans are shifting systematically from active participant and controller to that of monitoring and supervising machines. This shifting role is described aptly by Issac Asimov in his book *I Robot* (1950, p.52). The context of the following quote is a conversation between a scientist in the year 2057 and a robot who refuses to believe he was constructed by humans whom he regards as inferior. The robot speaks.

> "Look at you," he said finally, "I say this in no spirit of contempt, but look at you. The material you are made of is soft and flabby, lacking endurance and strength, depending for energy upon the inefficient oxidation of organic material-like that." He pointed a disapproving finger at what remained of Donovan's sandwich. Periodically you pass into a coma and the least variation in temperature, air pressure, humidity, or radiation intensity impairs your efficiency. You are makeshift. I, on the other hand, am a finished product. I absorb electrical energy directly and utilize it with an almost one hundred percent efficiency. I am composed of strong metal, am continuously conscious, and can stand extremes of environment easily. These are facts which, with the self-evident proposition that no being can create another being superior to itself, smashes your silly hypothesis to nothing."

NEXT GENERATION

What does the future hold for undersea habitats? Will man's place in the sea as a diver-aquanaut be usurped entirely by machines operated either remotely from the surface, from 1 atmosphere manned submersibles, or with the aid of 1 atmosphere diving systems? If the working depths are beyond about 300 feet (91.5 m), the answer probably is yes. With new machines providing engineering solutions to medical problems, the high cost of constructing and supporting deep diving saturation systems, including long and costly decompressions amounting to a little less than 1 day per 100 feet (30.5 m) of saturation depth, are making them noncompetitive with unmanned systems. Although there will continue to be a requirement for the specialized deep diver for a while, we believe that

ep diving saturation systems as we now know them will become almost scarce in the next few years as seafloor habitats are today.

At depths less than 300 feet (91.5 m), the future looks quite different. uman commercial divers will continue to enjoy a key role at depths not quiring expensive diving support systems. From the standpoint of afloor exploration, even within this relatively narrow depth range, there e alternative techniques to be considered. One is to build totally tonomous, self-propelled habitats, which in effect are laboratories within bmarines. This approach has been studied and attempted on several casions during the past 10 to 15 years. For example, a number of ulticrewed 1 atmosphere submersibles were built by private industry uring the 1960s, of which only a handful currently are operational Busby, 1976). They have been replaced by smaller special-purpose manned nd unmanned vehicles that incorporate the new technology.

The French partially constructed a large mobile laboratory in the late 960s named Argyronete and gave up due to high costs. In much the ame manner, the U.S. NOAA designed a mobile undersea laboratory in he 1970s called Oceanlab but cancelled it prior to beginning construc- on for the same reason. For the past 10 years the Institute of Oceanol- gy in the Soviet Union has been planning a mobile autonomous laboratory, o be named Chernomor-3. Work was stopped in 1979-1980 and as far as s known has not been renewed. Thus, it would appear that although a ophisticated, self-supporting, mobile habitat is perhaps the ideal solu- ion for manned undersea exploration, budget priorities are such that the evelopment of one in the immediate future is highly unlikely. As a onsequence, aquanauts in the near future will have to be satisfied with vorking in a limited area from semi-mobile habitats.

Home for the Marine Archeologist

An example of an activity suitable for relatively fixed habitats is the excavation of shipwrecks and historical undersea ruins. A shallow-water habitat located on the seafloor or suspended in midwater offers an ideal base from which the marine archeologist can map, study, and recover valuable artifacts. An instance where such a habitat would have been of immense value was during the salvage of a 1300-year-old Byzantine wreck in the Aegean Sea a few years ago. Because the wreck was located at a depth of 120 feet (36.6 m), divers could work on the bottom for only two 20-minute periods a day. The solution in this case to getting more work done was to find large numbers of divers (Burgess, 1980).

In the spring of 1977, the first project conducted by marine archeologists using saturation diving took place off the island of Lipari, northwest of the boot of Italy in 200 feet (60.1 m) of water. Rather than a seafloor

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All-Weather Laboratory and Classroom

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In addition to serving as research stations, seafloor laboratories suited ideally as classrooms in the wild in much the same manner as polar, forest, and desert stations. Some habitats already have been successfully for this purpose. For example, Hydrolab was used for sp marine science and diving training programs while in the Bahamas, 1971-1977 and provided the opportunity for student participation in sea programs in the U.S. Virgin Islands from 1978-1985.

In 1969, a habitat referred to as SEA-ROOM was conceived designed by William Marsden and George Peroni of Seatech Corpora Miami, Florida, expressly to fill the need for a small, inexpensive shelter for the diver-scientist (Fig. 10-5). SEA-ROOM was to be ma reinforced, high-strength concrete to house two divers at ambient sure or serve as a 1-atmosphere chamber at depths up to 200 feet (6 (Trillo, n.d.). The overall diameter of SEA-ROOM was 8.0 feet (2. with a height of 8.5 feet (2.6 m). The habitat was designed supported by steel legs on the bottom or to be moored beneath the su with an anchoring system. It contained a 30-inch (76.2 cm) dia hatch and three 12 × 24-inch (30.5 × 61.0 cm) ports. With an air v

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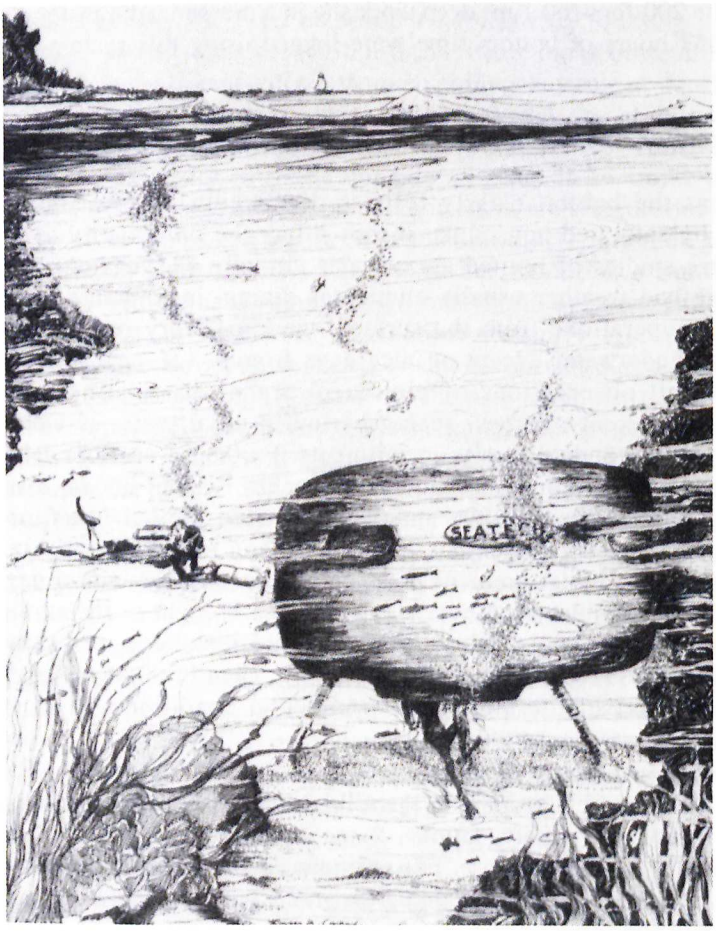

Figure 10-5. SEA-ROOM. *(Courtesy of Seatech Corporation, Miami, Florida.)*

of 8 tons, the habitat was transportable by air and could be emplaced on the seafloor by two divers. The life-support system included air, supplied from the surface or from an on-board regenerator, a CO_2 scrubber, a dehumidifier, an oxygen monitor, lights, and furniture etc. This small one-room seafloor apartment also could be used as a decompression chamber.

SEA-ROOM was designed with the aid of a computer model, and it was hoped at the time to build several for use by the scientific diving community. But a minimum of ten orders was needed to make the project economi-

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cally feasible, and only six orders were received. As a consequence, no SEA-ROOM habitats were built (Peroni, pers. commun.).

In the 1980's, NOAA developed the Aquarius habitat for use in the California kelp beds near Catalina Island. Construction of the 81-ton habitat was completed in 1986. Instead of California, it was deployed in 1987 at St. Croix in the U.S. Virgin Islands where it remained until 1989. Relocated to Key Largo, Florida, Aquarius again became operational in 1993.

The 43 × 13-foot (13.2 × 4 m) habitat (Fig. 10-6) has three chambers and supports six aquanauts to depths of 120 feet (36.5 m) for up to 30 days. Its rated internal pressure is 232 FSW (71.4 m). Aquarius sits on a 25 × 45-foot (7.7 × 13.8 m) baseplate containing leveling legs and uses a surface support vessel for operations and relocation. The habitat is equipped with freezers, seawater sinks, laboratory benches, and computer facilities. Communication systems include single-side-band radios, hard wire umbilical, hydrophones and emergency breathing/communication stations (see Fig.6-11).

The design for the Marine Resources Underwater Classroom/Laboratory was developed under the direction of Dr. Neil Monney at the United States Naval Academy as a senior design project for ocean engineering students. Conceived in 1970, the MEDUSA (Midshipman Engineered and Designed Underwater Studies Apparatus) project was planned to provide engineering design and project management experience for midshipmen, as well as to develop a safe and usable scientific research facility which would allow study of the Chesapeake Bay. Funding and equipment support was provided by the Navy Deep Ocean Technology Project.

The project proved to be an interdisciplinary effort with support provided by a broad spectrum of engineering students in the design of the various

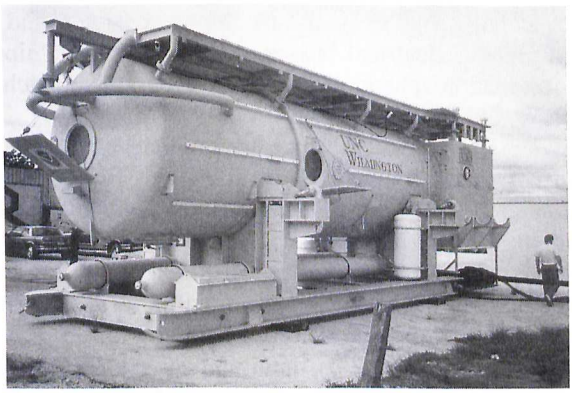

Figure 10-6. Aquarius. *(Courtesy of the National Oceanic and Atmospheric Administration.)*

subsystems. Although completed in 1980, the habitat was never used operationally and eventually was declared surplus.

The Marine Resources Development Foundation (MRDF) obtained the habitat and in January, 1984, transported the structure to Florida. MRDF soon began marine science and engineering programs to utilize the habitat in a sheltered lagoon in Key Largo, Florida as an undersea classroom/laboratory. More than 530 highly successful missions were carried out by the summer of 1995. These missions ranged in length from one to fourteen days and have included training and education programs for students, NASA Studies, NOAA Diving Research programs and biological research. A total of 1325 students have become aquanauts as a result of their experience in Marinelab.

Marinelab is a 16-foot × 8-foot (4.9 × 2.4 m) steel cylinder mounted horizontally on a steel and concrete cradle. A 66-inch (167 cm) diameter clear acrylic observation sphere is attached to and located beneath the lab (Fig. 10-7A). The sphere was developed by the Naval Civil Engineering Laboratory, Port Hueneme, California and designed for submerged operations to a depth of 1000 feet (305 m). Access to the sphere is from inside the lab, making it a dry observation area.

The support cradle provides a platform for the lab, protection for the observation sphere and ballast for the entire structure. Composed of I-beams, angle iron and concrete, the structure displaces approximately 35 tons.

With 22 tons of ballast, the facility has a positive buoyancy of 2000 pounds (907 Kg.), which allows the lab to float and then be towed to the site. Submerged concrete clumps are used for additional ballast. The lab is attached to the clumps with cables and the facility is winched down to the desired depth.

The laboratory is divided into three areas; the wet room, the main laboratory, and the observation sphere. The wet room includes the primary access hatch, a shower, portable toilet, and storage for emergency air tanks. The main laboratory area includes a galley (with sink, microwave oven, and refrigerator), three bunks, a dinette, electrical busses, communication equipment, access hatch to the observation sphere, an additional emergency hatch, and a large viewing port (Fig. 10-7B).

The main living and laboratory areas are separated from the wet room in order to control humidity and maintain a feeling of normal living accommodations. The walls of the lab are insulated with a closed cell, pliable foam insulation of the type used in U.S. Navy submarines.

The shore-support facility is housed in a 20-foot (6.1 m) long standard cargo container. An umbilical hose provides electrical power, compressed air, hot and cold water, and communications to the habitat.

Life support systems provided by the umbilical are designed to maximize both safety and reliability. Two low-pressure compressors, located in the support van, provide both primary and back-up air.

Temperature and humidity are controlled by an air conditioner in the habitat.

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Scrubbers are not necessary for the removal of carbon dioxide for regular missions because the flow of air is sufficient to continually flush the lab and remove all contaminants. Scrubbers are installed and available, however, for use during special biomedical studies.

Air quality is monitored continuously in the lab and in the support van. A water level alarm in the entry hatch signals any decrease in air pressure in the laboratory.

The primary purpose of the Marinelab is to provide the marine science community with a seafloor laboratory previously unavailable to large numbers of students. A four-phase program involving secondary school in-service training; secondary school exceptional student programs; community college marine science studies; and university undergraduate and graduate programs has been developed by MRDF.

Several missions have provided in-service training for Florida marine science educators to familiarize them with laboratory operations and to provide teaching materials and laboratory time for inclusion in existing marine science curricula.

High school student divers throughout the country have used Marinelab in conjunction with other MRDF programs. Course work specializing in the geology and biology of the Florida Keys prepares the students prior to habitat orientation and programmed laboratory studies.

University level programs provide opportunities for students and faculty to augment their classroom experience through the study of water quality, turbidity, current structure, and population densities within the lagoon.

Future work will include studies of marine corrosion, design of fish attraction devices, artificial habitats, aquaculture, mangrove lagoon ecology, shallow basin sedimentation, and water circulation.



Figure 10-7. A: Marinelab. Onshore. *(Courtesy of Ian Koblick.)*

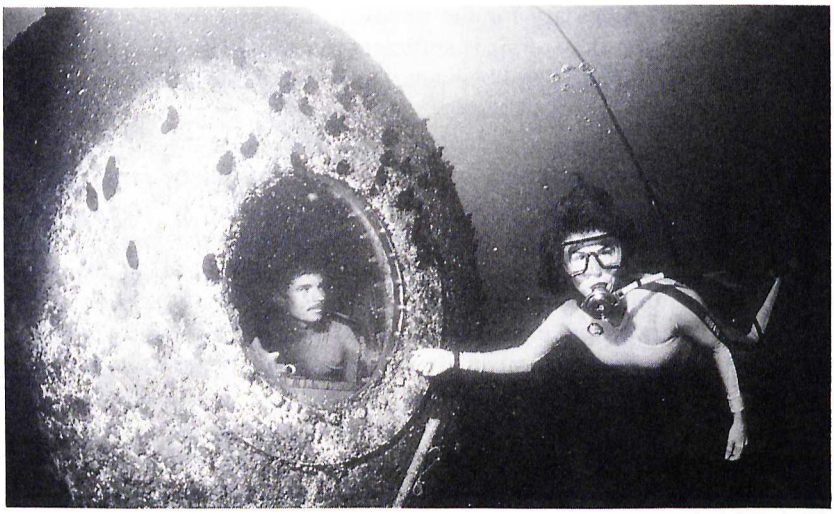

Figure 10-7 B: On seafloor. *(Courtesy of Robert Holland.)*

Other Habitats

Imagine yourself living in a floating igloo on the surface of a clear lagoon somewhere in the tropics or perhaps on the cool waters of a northern lake. The cable that moors your vacation home to the bottom also serves to transport you below the surface in a spherical glass elevator that you can stop at will to observe aquatic life. When tiring of this spectacular show, you simply return to your floating home, lounge on deck, water ski, or enjoy a meal. Pure fantasy? Not so! Such an arrangement is entirely practical and combines the safety of a 1-atmosphere environment on the surface with the ability to spend unlimited time observing the underwater world. In the 1960's, two researchers, C. Minot Dole, Jr., and Hank Chang, at Corning Glass in New York designed just such a vacation home. They used glass for the sphere and Styrofoam and plywood for the floating raft and igloo (Fig. 10-8). Power came from solar cells in the roof. Although floating cottages such as these may have been ahead of their time, modern technology makes them much more feasible now than when first suggested.

Others have suggested building sub-bottom stations carved into the ocean floor itself. Depending on location, the station could be connected to shore by a tunnel or contain a system permitting a submersible to mate and transfer people and supplies to and from the habitat. As an alternative to being located in the seafloor, such a structure could be installed on or within a submerged mountain or seamount such as the Cobb Seamount off the state of Washington.

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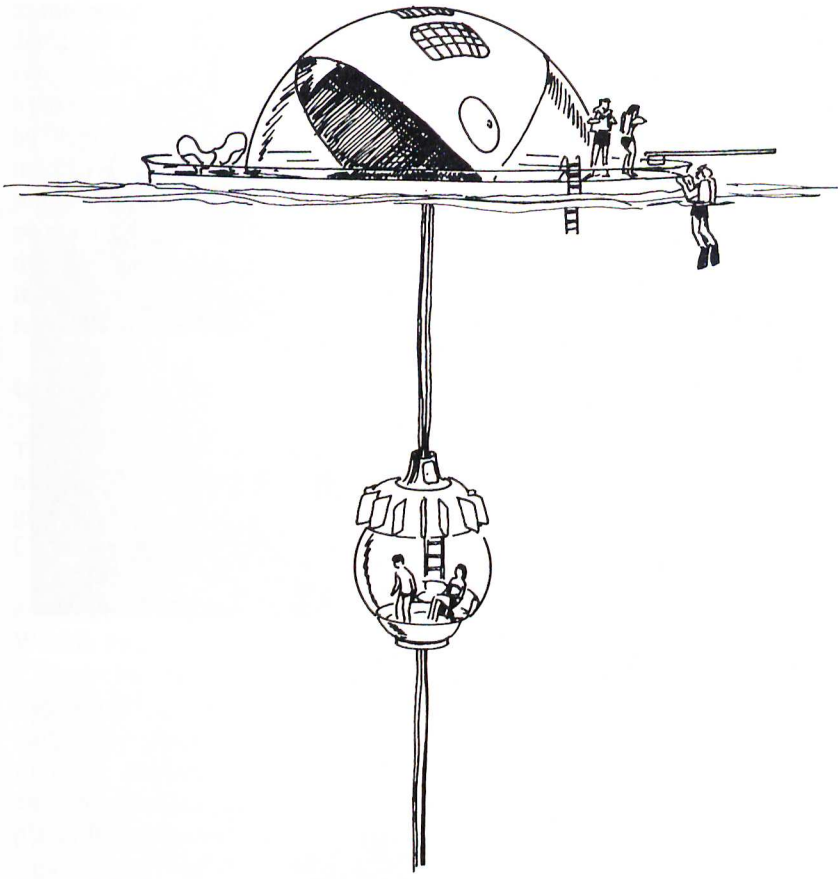
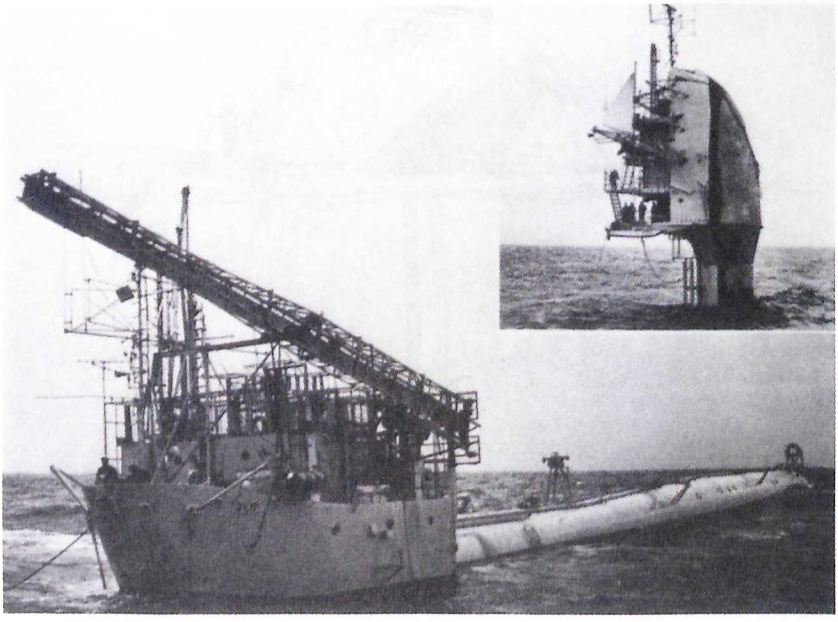


Figure 10-8. Floating cottage. (After an illustration by Dallison, which first appeared in Esquire, July 1966.)

Once installed, these subbottom structures could serve as permanent, weatherproof, scientific monitoring and research laboratories in the same manner as do wintering-over stations in Antarctica.

Yet another approach for underwater living and research is the 355-foot (108.2 m) Floating Instrument Platform (FLIP) used by Scripps Institution of Oceanography for several years (Fig. 10-9). In this case the vessel was towed to the site in a horizontal position looking much like any other vessel. Once on site, however, it was flooded in such a way that it assumed a vertical position, thus becoming a stable platform extending 300 feet (91.5 m) below the surface. Its occupants can live in comfort, record observations, and conduct acoustic and oceanographic research at selected depths from the surface



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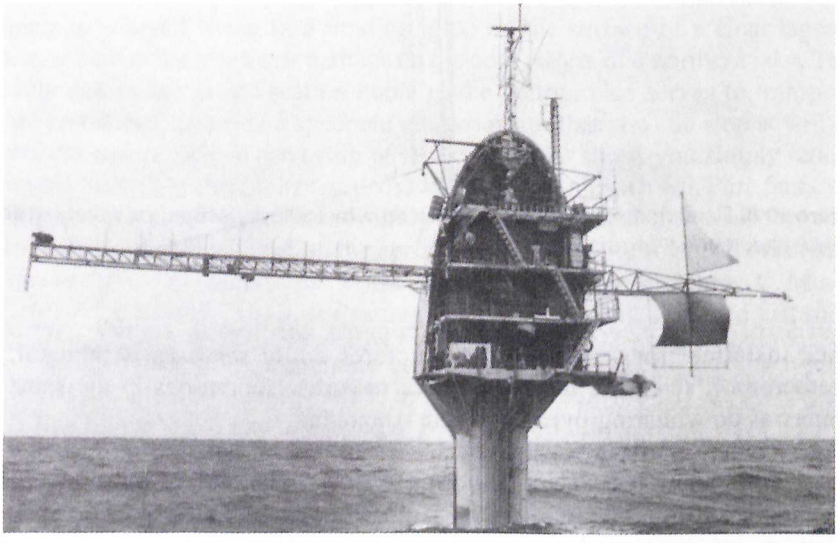

B

Figure 10-9. FLIP, a 335-foot floating instrument platform. A: In towing position; *B: Deployed in vertical position. (Courtesy of Scripps Institution of Oceanography, San Diego, California.)*

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to the bottom of the vessel. With modification, a FLIP-type vessel could be designed to permit divers to enter and exit the water through a double-lock entry at any depth. Further modification could provide an ambient pressure living and working area for aquanauts. Exactly this approach was proposed by Stepanov in the former Soviet Union some years ago (Repin, 1970). Whereas the FLIP vessel is a 1-atmosphere laboratory for oceanographic research, the proposed Soviet system was to be a diving system in which nine to twelve people lived at ambient pressure in the upper chamber and were transported to the work site using an elevator contained in the 328-foot (100 m) long vessel. It was anticipated that the system would support work to depths up to 1640 feet (500 m). Whether this vessel actually was constructed is not known.

Underwater Resort

The most likely use of seafloor habitats in the future is as a seabed resort hotel, clearly an idea whose time has come. Resort undersea habitats have a great potential for enhancing the business of ocean resorts throughout the Caribbean and the world.

The concept of undersea hotels is not new. A model of such a resort was exhibited at the General Motors pavilion during the 1964-1965 New York World's Fair.

Resort habitats provide a focus for enormous media attention. An overnight stay beneath the surface of the sea usually will be combined with a longer stay in the shore facilities. These habitats can be built in local shipyards and towed to their desired destination. Properly designed, they have minimal environmental impact (in fact they usually serve as an artificial reef). Once in place, they are inexpensive to operate if they are within easy reach of a life support umbilical from shore.

Jules' Undersea Lodge, the world's first seafloor resort, began operations in November 1986 in Key Largo, Florida. Prior to this time, the Lodge had been used as an undersea research habitat known as La Chalupa (see Figs. 4-41 and 4-46). After a series of remarkably successful missions off the west coast of Puerto Rico (see Pages 127-134), funding for the research programs ended, and in 1976 the habitat was towed to Florida where it was abandoned for several years in the Miami River.

In 1980, the habitat was purchased and partially refurbished for a treasure ship recovery project in the Caribbean. This project was cancelled in 1981 because the treasure ship was found to be under 30 feet (9.1 m) of mud and recovery was impractical. The partially refurbished habitat languished in a shipyard in Fort Lauderdale, Florida for another four years, until it was purchased in 1985 by Ian Koblick and Dr. Neil Monney.

Koblick and Monney redesigned and refurbished the habitat, converted it into an underwater hotel and named it after Jules Verne, the renowned science

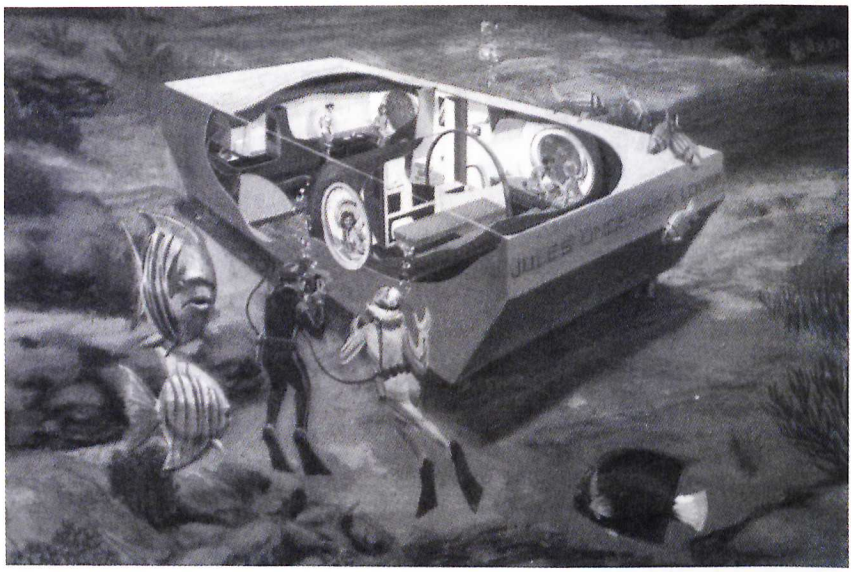

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Figure 10-10. Jules' Undersea Lodge. A: Cutaway; *(Courtesy of Key Largo Undersea Park.); B: Interior; (Courtesy of Robert Holland.)*

(Continued from front flap)

Table 10-1. Specifications of Jules' Undersea Lodge

Capacity	6 guests
Depth	bottom—30 ft hatch (saturation)—22 ft
Length Width Height	50 ft 20 ft 11 ft
Material	steel/acrylic
Foundation	(4) preleveled adjustable legs
Living chambers	(2) 8 × 20 ft (cylindrical)
Wet room chamber contents	diver "moon pool" entrance and exit enclosed shower/toilet living chamber—private entrances diving gear storage ceramic tile deck
Wet room dive port contents	5 × 7 ft diver entrance/exit via "moon pool" underwater seats and lights
Viewport windows	(3) 42-inch diameter, 4-inch thick acrylic ports
Accommodations	(2) 8 × 10 ft private bedrooms, one lower double bed one upper single bed (1) 8 × 20 ft dining/entertainment suite also contains two lower single beds used only when 5 or 6 guests book as a group (1) 10 × 20 ft dive and bath area
Amenities	sink/private refrigerator in bedrooms full bath in wet room complete mini kitchen dining and entertainment area commercial phone/intercom in bedrooms stereo/video/VCR in each bedroom VHF radio to surface control center

fiction writer of the 19th century (Fig. 10-10). Table 10-1 contains the specifications for the Lodge.

Following refurbishment (Fig. 10-11), the Lodge was towed to Key Largo, Florida and placed in the Marine Resource Development Foundation's (MRDF) three-acre (1.2 hectare), 30-foot (9.1 m) deep Emerald Lagoon. This lagoon already was home to the MRDF-operated Marinelab (See Fig. 10-7).

Although the lagoon depth is 30 feet (9.1 m), the depth of the Lodge diver entrance hatch, or saturation depth, is 20.5 feet (6.2 m). Because of this modest saturation depth, chamber decompression is not required prior to returning to surface pressure. A discussion of the concept of saturation diving and its no-decompression limits may be found on pages 15, 16, and 288.

Since becoming operational in November 1986, more than 1400 missions have taken place, ranging in duration from 1 to 69 days. Over 4000 residents of the Lodge have earned the title of Aquanaut (see page 28 for definition).

In addition to serving as a seafloor hotel, the Lodge has hosted several special projects, including La Chalupa 30, a 30-day NASA crew behavior study, in 1992. Over-lapping this study was Project Atlantis, a 69-day mission designed to raise awareness about ocean living. Managed by Mark Ward, the project attracted worldwide media attention as aquanaut Richard Presley set a new world record for seafloor living. From 1993 to 1995, NASA Bio-engineer Dennis Chamberland used the Lodge for NASA's ongoing OCEAN Project and on September 9, 1995, the Lodge was used by Scott Carpenter and Ian Koblick to speak with Mike Gernhardt on space shuttle Endeavour.

Since opening, the Lodge has been featured in thousands of articles and hundreds of radio and television programs. Attracted by such high profile, visitors describe the facility as a comfortable and attractive place to overnight.

While the most lucrative market will be divers, the dream of living in the sea will no doubt appeal to those seeking a unique experience. These seafloor vacationers will be able to share with aquanauts the unforgettable experience of becoming part of a strange new world. As aquanauts of the past have found, given ample time, fascinating and astonishing activities can be observed, with the once-hostile environment becoming a local petting zoo. One can become absorbed for hours watching those marvelous minute creatures that normally are passed over during short dives from the surface. After spending a few hours during the day diving and observing the antics of the marine neighborhood, a break can be taken for a leisurely gourmet dinner followed by an evening watching an altogether different succession of events colors, shapes, and sizes—a real Jules Verne experience.

Whether undersea communities where families work and play on the seafloor for weeks or months at a time will spring up remains to be seen. It is easy to let one's imagination run rampant where the household pet is a porpoise, the garden is full of seaweed, the hunting lodge is on an underwater mountain top, and the weather always is predictable. The technology is here today; it remains for us to use it tomorrow.

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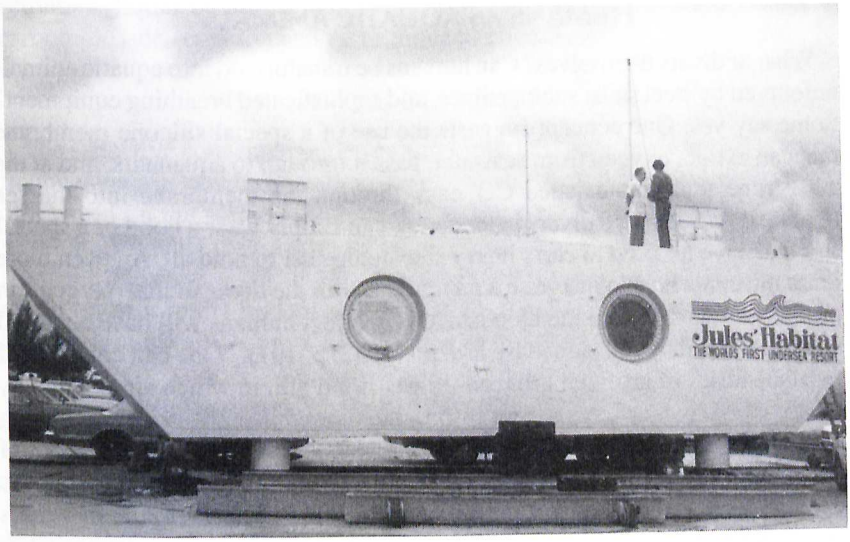

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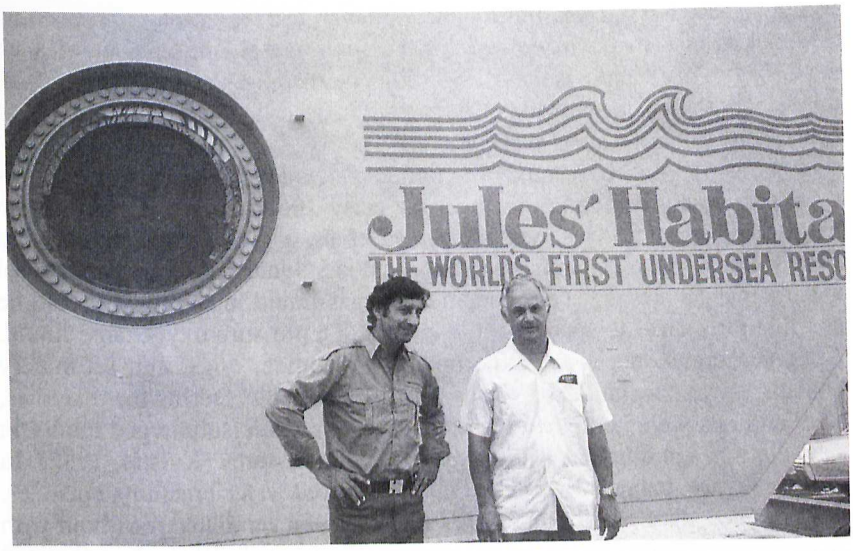

B

Figure 10-11. Jules' Undersea Lodge, with Authors Miller (white shirt) and Koblick during refurbishment at shipyard, Port Everglades, Florida. *(Courtesy of Miller and Koblick.)*

HUMANS AS AQUATIC ANIMALS

What of divers themselves? Can humans be transformed into aquatic animals unfettered by steel suits, submersibles, and sophisticated breathing equipment? Some say yes. One concept suggests the use of a special silicone membrane that can extract oxygen from seawater, pass it through to aquanauts, and at the same time transport exhaled CO_2 back through the membrane into the sea (Robb, 1965). Perhaps divers in the future can simply wear a hood or a special suit and have no need to carry heavy steel tanks just to hold air. An even more dramatic concept is to integrate a membrane with the diver so that oxygen can pass from seawater into the bloodstream. In effect humans will have acquired an artificial gill. As discussed by Kylstra (1982, p. 197), "One can conceive of two categories of artificial gills: one, a gas-filled gill, in which air exhaled by the diver exchanges oxygen and carbon dioxide with sea water before being reinhaled, and the other a blood-filled gill, which closely resembles the gill of fish and in which gas exchange occurs directly between the sea water and the diver's blood." The work leading to such concepts began in the early 1960s but was not initiated primarily for underwater application because it has considerable potential in the fields of medicine, biology, and chemistry where it is necessary to filter or separate one substance from another. Much more work is needed before the artificial gill becomes a viable alternative to our air-breathing habits. It is interesting to note, however, that researchers in the former Soviet Union also have worked on the underwater application of such technology. An example is the use of a silicone membrane for construction of the Selena-I habitat discussed in Chapter 9 and described in Russian literature as the habitat that breathes (Frantsen, 1974).

In another approach to converting humans to aquatic animals, experiments were performed, beginning again in the early 1960s, to see if mammalian lungs could move water in and out instead of air, with oxygen being extracted directly. Because the amount of gas dissolved in a liquid is directly proportional to the partial gas pressure at equilibrium on the gas-liquid interface, it should be possible for a diver to survive while breathing a pressure-oxygenated liquid. After numerous successful experiments with mice, dogs, and ultimately humans, it was concluded that the concept was possible. During these studies, mice and rats were kept alive for up to 18 hours while submerged totally in salt solutions equilibrated with oxygen at high pressures (Kylstra, 1982). In the years since, many animals have safely survived water-breathing episodes. For example, all of a series of 36 dogs who had been ventilated for 1 hour with an oxygenated fluorocarbon liquid survived (Model et al., 1971). Anesthetized humans have survived experiments in which one lung was ventilated with a physiological salt solution at normal body temperature. The main question to be answered is not whether a liquid can be used as a breathing medium but whether a method of effectively eliminating the carbon dioxide produced can be developed. According to Kylstra (1968, p. 48), "In human underwater

(Continued from front flap)

activities, liquid breathing will be possible only if the untoward effects of carbon dioxide retention can be minimized effectively."

CITIES IN THE SEA

The seductive concept of undersea cities long has been the subject of science-fiction novels in which generations experience birth, life and death not knowing of a world on the surface. Without doubt, the marvels of today's science and technology could create such a city with power from the atom, food and water from the sea, and sturdy walls to fend off the pressure. Figure 10-12 is a rendition of a future underwater community as seen through the eyes of the visionaries at Walt Disney's EPCOT Center in Orlando, Florida.

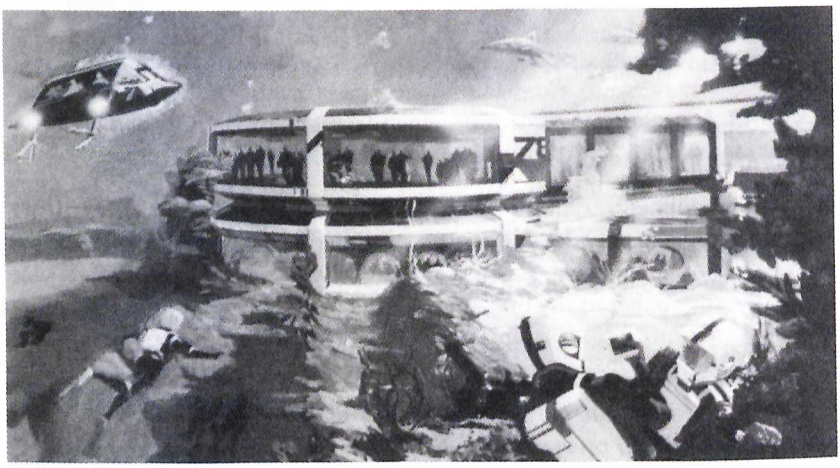

Figure 10-12. The Living Seas-EPCOT Center. *(Copyright Walt Disney Productions.)*

Although no undersea cities have been built to date, there are serious plans for large undersea resorts. One such project is planned for Panama at the Pacific end of the Panama Canal, across from the Bridge of the Americas. An ambitious plan created by Jose Rogelio Arias, Jr., the former Director of Tourism for Panama, is underway to develop an undersea city as an attraction and focus for three large theme parks, a casino and a cultural park. The undersea city portion of this billion dollar project would have more than 400 hotel rooms underwater, in addition to underwater restaurants, theaters, retail stores, a large conference center, and a casino (Fig. 10-13). The project would require a considerable engineering effort to overcome difficult natural conditions consisting of 16-foot (4.9 m) daily tides and water with limited visibility. The construction techniques, however, are straight forward and the end product should be a beautiful land and sea-based facility comprising the world's first undersea city.

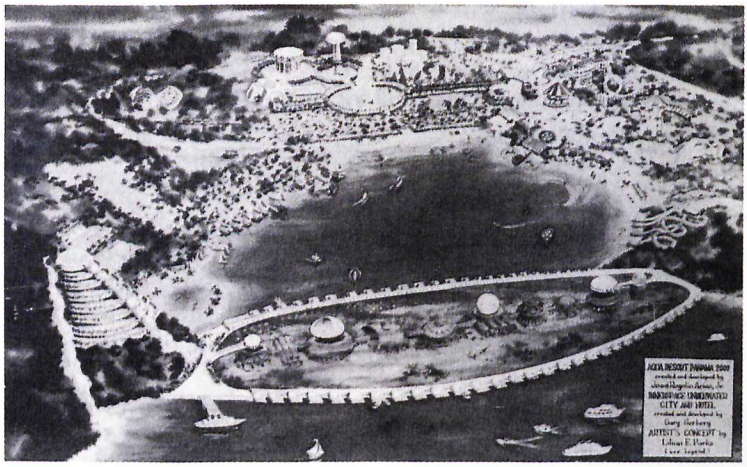

Figure 10-13. Aqua Resort Panama 2000, Innerspace Underwater City and Hotel *(Courtesy Panama 2000.)*

An earlier concept combining the technology of offshore oil-drilling platforms and undersea technology was exhibited at Expo '75, International Ocean Exposition, Okinawa, Japan in 1975. Called the AQUAPOLIS, it was billed as the forerunner of floating cities. Using 16 floodable pillars, this large multi-story platform could be submerged to or raised from a depth of 49.2 ft (15 m) by regulating the amount of water in its lower hull. To the best of our knowledge, the concept was never carried beyond the construction of the full-scale model exhibited in 1975. If one thinks on a scale smaller than the AQUAPOLIS or the Panama undersea resort project just described, a potential need that comes to mind is the use of seafloor facilities for ocean farming. The worldwide shortage of food has radically increased the rate of development of both fresh water and marine aquaculture. It is not difficult to envision shellfish farmers or other aquaculture specialists living on the seafloor for weeks at a time tending their "crops".

In 1973, French architect Jacques Rougerie designed, for the University of Hawaii and NOAA, a plan to build a subsea village, intended for use as an astronaut training facility (Fig. 10-14). The futuristic design called for a large central section constructed of ferroconcrete to be used as living quarters for the up to 250 projected inhabitants. Surrounding this hub were to be several ambient pressure structures, each anchored to the seafloor, in a design inspired by the "argyronet", or water spider. These pods were also to serve as living quarters for the village's resident fish-farmers.

While this futuristic concept remains on the drawing board today, many of Rougerie's visionary designs have taken shape in the past. His "Galathée" habitat was built in 1976 and was first put into service underwater in 1977

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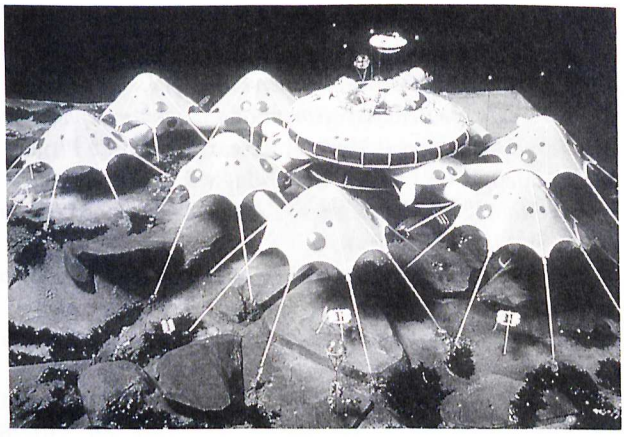

Figure 10-14. Subsea village design *(Courtesy of Jacques Rougerie)*

(Fig. 10-15). The semi-mobile, oblong structure consisted of a steel hull and methacrylate domes oriented towards the surface. It was designed to accommodate 4 to 6 aquanauts during planned stays of up to 90 days.

At the risk of shattering the dreams of some readers, however, we think that the likelihood of permanently inhabited undersea cities comparable to even small towns on land, is an idea whose time has not come. The reasons? Cost, the lack of a real need, and the priorities of a world faced with health, economic, and political issues affecting our survival. Humans will continue to enjoy the sea, use its resources, play on its shores, sail on its surface, and venture beneath it. Visits will be made to seafloor laboratories and classrooms for days, weeks, or even months at a time by those wishing to learn more of the secrets of the sea. Seafloor resorts will make it possible for those seeking the ultimate vacation experience to learn more about and enjoy the sea at its best. For all of us, the sea will forever be a source of wonder and inspiration. Let us learn to appreciate it to the fullest and to use it wisely.

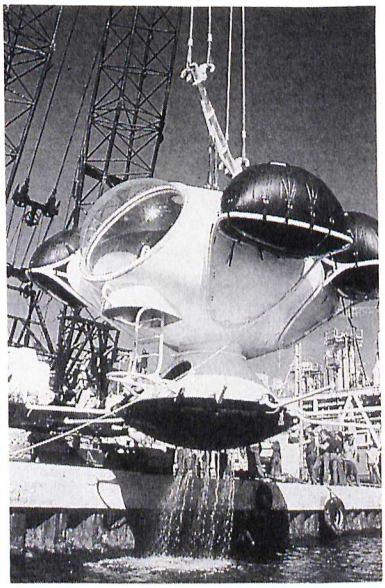

Figure 10-15. The Galathée habitat *(Courtesy of Jacques Rougerie)*

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Glossary

Absorbent: a nonregenerative chemical agent used to remove carbon dioxide from the surrounding atmosphere.

Aquanaut: a person who has lived on the seafloor for at least 24 continuous hours.

Atmospheric pressure: pressure exerted by the earth's atmosphere, which varies with altitude above sea level; at sea level, atmospheric pressure is equal to 760 mmHg or 1.03 kg/cm^2 (14.7 lb/in^2).

Bends: an imprecise term denoting any form of decompression sickness.

Blowup: inadvertent, uncontrolled, and rapid diver ascent when wearing a deep sea or variable-volume diving suit.

Deck Decompression Chamber (DDC): a hyperbaric chamber located on a surface platform from which diving is conducted or supported.

Decompression: in diving, that phase in which the individual is ascending in the water or is in a chamber when the pressure is being lowered.

Decompression sickness: a physiological condition caused by too rapid a reduction in pressure having a variety of signs such as itching, joint pain, disorientation, shortness of breath, and paralysis.

Diving bell: a tethered underwater support platform providing life-support services and used to transport divers.

Electrowriter: a device incorporating a writing pen (or stylus) on each end of a wire such that a message written using one pen is duplicated by the other pen.

Embolism: gas bubbles in the arterial system caused by gas or air passing into the pulmonary veins after rupture of the alveoli.

Equivalent air depth: the air breathing depth that has a nitrogen partial pressure equivalent to that at the diving depth.

Excursion diving: movement of a diver either vertically or horizontally, from the work platform, bell, chamber, or habitat at the saturation depth.

Grid system: a system of lines, markers, and/or direction indicators used on the seafloor to orient a diver for reasons of safety or scientific data collection.

Helium unscrambler: an electronic device designed to render intelligible the words spoken in a hyperbaric helium environment.

Hookah diving system: a system comprised of a hose and a breathing media supply source) a compressor or gas bank) that provides the breathing media to a demand regulator carried by the diver.

Hydrostatic pressure: The pressure of a column of water acting on a body immersed in the water, equal in all directions at a specific depth; it increases at a rate of 0.445 psi per foot of descent (1 kg/cm^2) per 10 meters in fresh water.

Hypothermia: reduction of body temperature as a result of environmental exposure to cold or failure of the body's thermoregulatory system.

Life support system: a system designed to produce a controlled environment for chamber or habitat occupants. May include capability to supply metabolic oxygen, control temperature and humidity, and remove CO_2.

Lock-out submersible: a submersible that has a compartment maintained at one-atmosphere pressure for the pilot or observer, and a compartment that can be pressurized to ambient pressure so that the diver(s) can enter and exit (lock out) while underwater.

Narcosis: in diving, a state of stupor or unconsciousness caused by effects of gases breathed at pressure. Symptoms may include light headedness, loss of judgment and occasional euphoria.

Nitrox breathing mixture: a breathing mixture containing nitrogen and oxygen in various proportions used in diving when the oxygen partial pressure must be reduced because of the depth of the dive and the danger of oxygen poisoning.

Normoxic breathing mixture: a mixture in which the proportions of breathing gas are selected to provide a partial pressure of oxygen that is close to, or slightly above the normal atmospheric value of 0.21 ATA at a specified depth.

Partial pressure: the proportion of the total pressure contributed by a

single gas in a mixture of gases. It is in direct proportion to its percentage of the total volume of the mixture.

Personnel transfer chamber (PTC): a capsule to transport divers between the surface and the work site that can be mated to the deck decompression chamber (DDC). Can be maintained at one atmosphere or pressurized depending on the type of system used.

Pressure vessel: an enclosure, usually of steel or aluminum, designed to withstand internal or external pressure or both, such as a recompression chamber.

Remotely operated vehicles (ROV): the ROV can be tethered-free swimming, bottom crawling, towed, or untethered and is used as a a method of achieving underwater work or data gathering.

Saturation diving: a term denoting a state in which the diver's tissues have absorbed all the nitrogen or other inert gas they can hold at that particular depth. Once saturation has occurred, the amount of decompression time required at the end of the dive does not increase even if the diver spends additional time at that depth.

Scrubber: a chemical/recirculation system used to remove carbon dioxide, odors, and trace contaminants from the surrounding atmosphere.

Trimix: a gas mixture involving three gases, usually oxygen, helium, and nitrogen.

Umbilical: The composite of hoses and lines supplying life support to the diver or habitat.

Variable-volume dry diving suit: a dry diving suit with both an inlet gas valve and an exhaust valve, so that together with the weighted belt, the diver can maintain buoyancy control.

Wet submersible: a free-flooding submersible in which the occupants are exposed to the ambient environment.



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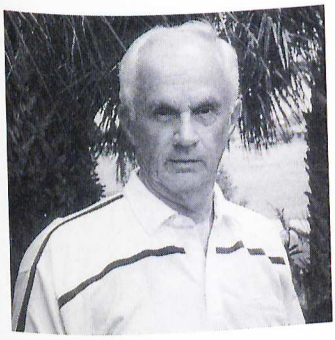

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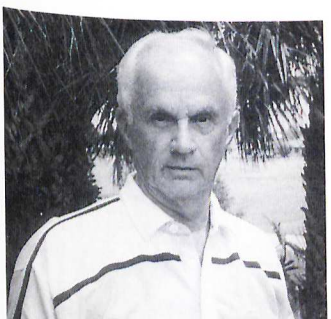
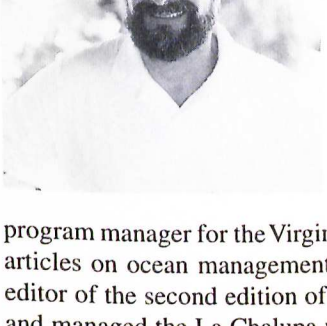


JAMES W. MILLER received the B.A. M.A. (1950) and Ph.D. (1956) in physi psychology from Michigan State Uni After twelve years of research in physi optics and visual display systems at the Eye Institute and Hughes Aircraft Comp joined the Office of Naval Research in director of engineering psychology. In became responsible for the diver perf studies in the U.S. Navy's Sealab-II a Sealab-III programs. Dr. Miller served a program manager of Tektite-I in 1969 and as program manager of Tek 1970. From 1971 to 1980, he was the deputy director of the NOAA Undersea Science and Technology Office. He participated as an aquana leader in a two-week saturation diving mission in 1973 and again in 1974 the La Chalupa habitat. In addition to authoring and co-authoring over 100 s and technical publications, Dr. Miller was the writer and editor of the editions of the NOAA Diving Manual and a consulting editor for the third The recipient of numerous professional awards, Dr. Miller served from 1985 as Associate Director, and from 1985 to 1990 as the Florida Keys Coo of the Florida Institute of Oceanography. From 1982 to 1992, he was a co and President of Woodell Enterprises. Since 1991, he has served as Vice C and member of the Federal Florida Keys National Marine Sanctuary Advisory



IAN G. KOBLICK, president of Resources Development Foundation sin is an international authority in underse He received a B.A. in biology from C State University at Chico in 1964. He h as special assistant to the Governor of t Islands for undersea programs and a advisor for the development of marine under two governors of Puerto Rico. Mr was an alternate aquanaut on Tekt aquanaut on Tektite-II, and served as program manager for the Virgin Islands' Government. He is responsible f articles on ocean management and resource development and was a c editor of the second edition of the NOAA Diving Manual. Mr. Koblick and managed the La Chalupa undersea habitat program and has spent n two months saturated in undersea habitats. Since 1984 he has operated and the Classroom in the Sea-MarineLab Habitat in Key Largo, Florida and owner and developer of the Jules' Undersea Lodge, the world's first un hotel. In 1995, he developed the Scott Carpenter Man in The Sea Program on experience using high-tech diving systems and equipment.