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MAN'S DEEP-DIVING CAPABILITIES AND LIMITATIONS (U)

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ABSTRACT OF

MAN'S DEEP-DIVING CAPABILITIES AND LIMITATIONS

This study deals with the problem of determining man's deep water capabilities as a free diver and the importance to the U.S. Navy of his role in this capacity.

Man has been diving into the sea for food and wealth prior to the beginning of written history. Until the advent of the diving bell in the fourth century B.C., his underwater activities were carried out without the aid of any mechanical instruments. There was a gap of almost 1900 years before improvements were made to underwater diving gear. From the nineteenth century until the present time, tremendous strides have been made in perfecting diving equipment. Yet it was only twenty five years ago, with the invention of the aqualung, that man was able to break his bonds with the surface.

Diving physiology and physics are under intense study by civilian and military scientists. The comprehensive program outlined by the U.S. Navy's Deep Submergence Systems Review Group has as one of its goals: perfection of equipment and techniques that will allow men to live and work on the ocean floor at 600 to 1,000 foot water depths for several months at a time. This goal is encompassed in the "Man-in-the Sea" program which applies the concept of

saturation diving. It appears that more thorough use of saturation diving is forthcoming since this diving method seems to be the best tool for prolonged deep water work.

It is the thesis of this study that man is on the threshold of "inner space." The new methods of diving will help open up the seas to the unenclosed, unencumbered, free diver.

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INTRODUCTION

The virtually untapped resources of the sea and the future potential of undersea activities and developments present a challenge that the U.S. Navy is fully regarding. It is the purpose of this paper to examine the importance of deep-diving in its future role in the Navy and to investigate the physiological limitations of man underwater.

The scope of this study includes activities where man is actually in or under the water and subject to the ambient conditions of his environment. This excludes activities where man is inside an underwater vehicle, but does not exclude the use of a submersible dwelling, diving cylinder, or other means that would enable him to act as a free diver.

Progress in man's attempt to conquer the depths has been painfully slow. Lack of proper equipment and limited knowledge of his physiological and psychological capacities, until recently, has held man to relatively shallow water depths.

The desire to spend hours, days, or even months at a time near the ocean floor at water depths of 600 feet and deeper has led to the concept of saturation diving. This concept of saturation diving or extended diving rests upon all the past knowledge of diving technology.

This paper provides a summarization of the history of diving. It outlines the threats to human physiology and human physical responses in the underwater environment. It compares conventional to saturation diving, and in the last chapter, discusses future oceanological prospects, as they apply to the U.S. Navy and to the United States.

MAN'S DEEP-DIVING CAPABILITIES AND LIMITATIONS

CHAPTER I

HISTORY OF DIVING

Early Divers. Evolution teaches that life began in the waters of the earth, and man through the millennia has been drawn to submerge himself in his primordial element. Both archeology and the written word testify to man's long history of diving into the sea. These divers of early times either sucked air into their lungs and plunged to the depths, or expelled air from their lungs and sank to the bottom. Today's divers may do the same thing for sport, but for the business of deep diving, professionals now have a vast array of equipment and knowledge to aid them in their job.

The evidence of ancient diving is obvious after a look at the marine products used by the ancient Greeks. These included bottom-dwelling animals that could be harvested properly only by divers. Mother-of-pearl, which cannot be gathered in any quantity without diving for the shells, has been found in carved ornaments in excavations of Sixth Dynasty Thebes, about 3200 B.C., and has also turned up in Mesopotanian diggings dating to 4500 B.C. (1:27)

In Homer's Iliad, written sometime between 900 and 700 B.C., Patroklos referred to diving among the Trojans at the time of the Trojan Wars. This could be interpreted as a use of divers for a military purpose. Certainly the feats of Scyllus and his daughter, who, it is stated, dived to free the anchors of the warships of Xerxes, can be considered military applications of diving. (19:4)

In this same frame of reference, the Syracusans are credited with training divers to swim underwater to damage attacking ships. Thucydides (471-400 B.C.) tells also how the Syracusans built underwater palisades outside the harbor to impale enemy ships. (8:548)

The Diving Bell. Aristotle in the fourth century B.C. writes of the use of a diving apparatus--a kettle or diving bell--by the local sponge divers. A diving bell is classified as a self-contained underwater breathing apparatus or scuba. The principle of a diving bell is rather simple. A bell-shaped container that is weighted in some manner to prevent tipping is lowered into the water so that air is trapped inside. A person can stay inside the container until the good air is used up. The diving bell was the dominant feature in the history of breathing apparatus for 22 centuries, until about 1800.

After Aristotle there is a gap of nearly 1900 years before the next known reference to a diving bell. Charles V, ruler of the Holy Roman Empire in 1538, at Toledo, Spain watched two Greeks descend to the bottom of the river Tagus in a diving bell. The importance attached to this event is that it was a successful demonstration of a diving bell which was witnessed by the most important person of that day. (8:604)

By the late 1600's bells were becoming rather refined, with internal platforms and tools. An Englishman, William Phipps, was knighted for using one to recover the Crown's sunken treasures. The most significant bell of the times was patented in 1691 by the English astronomer, Edmund Halley. The unique characteristic of his bell was a scheme to replenish the air inside. Lead-lined barrels were to be lowered alternately to transport fresh air to the bottom, where the fresh air could be vented into the bell. The bell contained a valve in its overhead to discharge the used air. (13:22) Halley's patent signaled the end of the diving bell as a self-contained technique. It was a small step to substitute a pump and hose for Halley's barrels. When this happened the bell became a caisson and a man could work for long periods underwater, but had very little mobility.

The Diving Helmet. The answer to mobility was the diving helmet. Helmet-hose diving was introduced in 1774. In Le Havre, a Frenchman, Sieur Freminet, demonstrated a helmet-hose or "hard-hat" diving apparatus in which air was supplied by a large bellows system on the surface. Helmet-hose diving prevailed for the next 170 years. (19:11)

In 1782 HMS "Royal George" capsized and sank at Spithead, England. It was for the "Royal George" salvage operation that the Englishman Augustus Siebe developed and perfected a diving helmet in 1819. This was originally a helmet without dress. The trouble with this was that the diver had to be very careful not to tilt over too far and lose his air. By 1837, still working on the "Royal George," Siebe modified his rig to the closed dress type. In this, a diver was fully clothed in a canvas dress, to which was bolted the helmet and breast plate. (8:405) This same apparatus, with improvements in its detail, is still used today.

The diving helmet enabled its user to increase the depth to which he could descend. In 1906, two members of a British Admiralty team under the supervision of John Scott Haldane of Cloan, Scotland, reached depths of 180 and 210 feet respectively. (31:85)

A report by George Stillson and Dr. G. R. French, dated 10 December 1914 and published by the Bureau of Construction and Repair in 1915, was a milestone in the U.S. Navy's Deep Submergence Program. In 1915 the submarine U.S.S. "F-4" sank to 304 feet in Hawaiian waters. Navy diver Frank Crilley reached her in a dive rarely matched again by a helmet man breathing compressed air. (10:57)

Closed-Circuit Scuba. From 1837 on, the progress of diving became dependent on the engineering of equipment, such as air compressor development. Through science, an understanding of diving physiology was ready to be born.

The diving bell is described as an attempt at using a self-contained underwater breathing apparatus. Leonardo da Vinci, circa 1500, devised, on paper at least, a self-contained underwater diving and walking suit. This, as well as the apparatus described by Giovanni Borelli in 1679, was impractical, but the theory of air regeneration by Borelli was a weak start in closed-circuit scuba. (19:13)

In 1835, Charles Condert from Brooklyn developed the first successful closed-circuit scuba. He used it repeatedly in 16 to 20 feet of water, but was drowned when his air tube broke and he was unable to surface. (19:15)

Siebe, Gorman, a British firm, claims to have marketed the first practical closed-circuit unit in 1878. This was the Fluess-Davis apparatus. (8:370) Fleuss tested an oxygen-rebreathing device in 1879. (10:31) There were several other closed-unit oxygen scuba developed along the lines of the Fleuss-Davis device. The Momsen-lung used as a submarine escape device was of this family. In Italy the Perelli single-hose oxygen scuba became the standard for attack swimmers during World War II. Dr. Christian Lambertsen of the University of Pennsylvania developed a streamlined, lightweight, closed-circuit oxygen apparatus in 1941. In 1950 he developed an improved mixed-gas model called Flatus. Two Lambertsen units are the direct off-spring of these--the present U.S. Navy Mark V and Mark VI mixed-gas scuba. (31:92)

Open-Circuit Scuba. Commandant Yves le Prieur devised an air lung in 1926, and an improved version in 1933. In the later version a full face mask replaced the goggles, mouthpiece, and nose clip of the earlier model. The major apparatus consisted of a compressed air bottle slung on the chest with an air pipe to the full face mask. (10:27) About this same time swim fins were developed. So for the first time men could try to really act like fish.

Yves Cousteau made the first successful sea tests of the fully automatic scuba, created by himself and the engineer, Emile Gagnan. It supplied compressed air on demand to the human respiratory system at the correct depth pressure. In October 1945, off the coast of Marseilles, Frederic Dumas, an associate of Cousteau, dived to a depth of 220 feet for an elapsed time of 15 minutes, using the new Cousteau-Gagnan scuba. (4:179)

In 1946, the Cousteau-Gagnan "aqua-lung" appeared on the civilian market. For a tremendous number of people it proved to be the passport to inner space. Yet for various reasons, men using compressed air cannot perform reliably much below 200 feet. It was now up to science to find new breathing mixtures if men were to go deeper.

Exotic Gases. In 1919 Professor Elihu Thompson contacted the U.S. Bureau of Mines suggesting that helium be used in place of nitrogen in the breathing supply of deep divers. The Bureau joined with the Navy and a mine safety company, and in 1925 deep-diving experiments began at an experimental station in Pittsburgh, Pennsylvania. Animals, then humans, breathing 80 percent helium and 20 percent oxygen, were tested in compression chambers. (36:51)

A U.S. Navy Experimental Diving Unit was established in Washington, D.C. in 1927. The E.D.U. embarked on an exhaustive program of test dives, equipment redesign, and general research in the field of diving physiology. A system of diving using helium was put to use in 1939 when the submarine "Squalus" sank in 240 feet of water off Portsmouth, New Hampshire. (31:86)

Following the lead of Navy physiologists, a young engineer named Max Gene Hohl decided to test the use of helium and oxygen. In December of 1937, on Lake Michigan, Nohl reached a new record depth of 420 feet. (10:59)

Captain W.O. Shelford, Royal Navy Diving Superintendent, organized a series of dives to see how far divers could go in the event of deeper submarine sinkings. He had a driving urge to bring the deep-diving record to Great Britain. Using a helium-oxygen combination, Wilfred Bollard, a petty officer of the HMS "Reclaim" attained the record at 540 feet in 1948. (10:63)

A 28-year old Swedish engineer named Arne Zetterstrom attempted during World War II to tame hydrogen and breathe it in great pressure. In August 1945, he made a dive to 528 feet. Zetterstrom died after reaching the surface. An inquiry showed that he died because two of the line handlers at one end of the parent ship pulled him too rapidly to the surface from a depth of 100 feet. Even though the cause of death was not attributed to the hydrogen-oxygen apparatus, no one has continued his experiments with hydrogen. (10:73)

Deepest Dive. Hannes Keller and Albert Buhlmann, M.D. from Switzerland, evolved a deep-diving theory based on changing the proportions of nine gases during vertical round trips far past the 200-foot working stratum of compressed-air divers. In 1959, Keller developed tables for dives to 1,312 feet. With the help of Yves Cousteau, Keller made two simulated dives, the latter to 1,000 feet. He and Kenneth MacLeish dived to 728 feet in Lake Maggiore, Switzerland in 1961. (25:66-71) In December 1962, Keller and Peter Small, a London journalist, attempted a 1,000-foot dive in a chamber of his own design. At a depth slightly exceeding

1,000 feet Keller briefly went out of a bottom hatch, while breathing from an air hose, and planted the Swiss and American flags. Reentering the bell, he caught part of a rubber fin in the closed hatch and lost airtight seal on the chamber. Both divers passed out, but Keller revived on the way up. Peter Small died soon after reaching the surface. (9:44)

Many dives below 1,000 feet have been made by men in bathyscaph vehicles such as the "Trieste," but Keller's dive has been the deepest so far by a diver in his hydrostatic pressure environment. In other words, Keller and Small were not in a pressurized cabin, but were subject to the tremendous external pressure of the water at 1,000 feet. At sea level the ambient, or surrounding, pressure of air is 14.7 pounds for every square inch it covers. At 1,000 feet the ambient hydrostatic, or surrounding water, pressure is 459.7 pounds for every square inch of body surface. According to many authorities, the extraordinary dive of Keller and Small will soon be an ordinary, everyday accomplishment.

CHAPTER II

DIVING PHYSICS AND PHYSIOLOGY

First Scientific Explanation. Ancient divers knew that there were limits and dangers beneath the sea, but a partial scientific explanation of man's physical behavior under pressure did not come until about 80 years ago. In 1878, Paul Bert, a French physiologist, looked into the breathing problems of high balloonists. After thoroughly delving into altitude physiology, he began to study the physiology of man subject to the pressures of the sea. Bert studied the clinical reports of Dr. Alphonse Gal. Dr. Gal was the first medical man who actually dived to study men under water. Bert's findings demolished all previous diving theories, none of which was based on scientific knowledge. Bert said, "Pressure acts on living beings, not as a direct physical agent, but as a chemical agent changing the proportions of oxygen contained in the blood and causing asphyxia when there is not enough of it or toxic symptons when there is too much." (10:48) He found that breathing pure oxygen was fatal in high pressures. His most important discovery was the effect of nitrogen breathed under pressure, which explained "the bends" for the first time. (10:48)

In 1906, John Scott Haldane took up where Bert had left off. He headed a group commissioned by the Admiralty to study diving. This team of Haldane, Boycott, Damant, and Catto wanted to turn Bert's work into systematic knowledge. Paul Bert showed that divers did not suffer the bends when drawn from 33 feet to the surface. Haldane said that he could therefore haul a man from six atmospheres (units of 14.7 pounds per square inch) to three with no danger. The trick was to halve the pressure. From great depths he would halve the pressure of a diver in stages. The diver would be suspended for periods at each stage to pass off dissolved nitrogen. This was the discovery of underwater stage decompression, the safeguard of all divers since. (10:58) Decompression and recompression are the subjects of Chapter III.

At this point in the discussion, a look should be taken at the physical environment of the diver, and how he is affected by it.

Physical Environment. Atmospheric air is a gaseous mixture composed of 79 percent nitrogen (N_2), 20.94 percent oxygen (O_2), .03 percent carbon dioxide (CO_2), and .03 percent rare gases. Air is the primary limiting factor in free diving. A diver breathing compressed air cannot surpass the depth of 300 feet without incurring the gravest risks. Air divers are not very effective at accomplishing a task below 200 feet. The limits stem mainly from the body's ability to adjust to the physical effects of breathing air under pressure. (20:96)

At sea level, the air in the atmosphere weighs 14.7 pounds for every square inch of surface it covers. Pressure measurements are reckoned in "atmospheres"--as noted, these are of 14.7 p.s.i. (pounds per square inch). (20:96) In other words, a person existing at sea level is under the pressure of one atmosphere.

Pressure, whether expressed in total pounds, or pounds per square inch (p.s.i.), is referred to as ambient pressure which is pressure transmitted to a body equally from all directions in matter in which it is immersed.

Water Density and Boyle's Law. Water is almost 800 times heavier and denser than air at sea level. One cubic foot of sea water weighs 64 pounds. A column of sea water measuring one square inch by 33 feet weighs the same and transmits the same amount of pressure as a one-square-inch column of air that is as high as the stratosphere. Since water and air pressure is exerted on a body equally in all directions, a free diver swimming 33 feet beneath the surface is subject to a pressure equal to the weight of the column of sea water above him plus one atmosphere. Like air pressure, water pressure is a direct result of its weight. In comparison to air, however, water is practically incompressible and the denity virtually unchangable. Therefore, unlike air, which is compressible, water pressure increases in direct proportion to its depth. (20:100) Water pressure increases 14.7 p.s.i. every 33 feet of depth. Since 33 feet deep is two atmospheres, then 66 feet deep is three atmospheres, 99 feet deep is four atmospheres, and so forth.

It is important to remember that it takes only 33 feet in depth to double atmospheric pressure. It takes an additional 66 feet to double it again. This realization shows that percent changes in pressure are largest near the surface. (16:104)

In hydrospace or underwater environment, the increased density of water is obvious to the diver at once. Movements are opposed by the frictional force, or viscous drag, of the water. At ordinary temperatures this drag is more than 50 times greater than the drag in air. (16:109) The density of matter refers to its weight per unit of measure. Gases have fewer molecules per given volume than solids, so have less density. Gas molecules can be compressed closer together much more easily than can molecules of other matter. The phenomenon of compression is expressed in Boyle's law, in which the Irish physicist Robert Boyle stated that "at a constant temperature, the volume of a gas will vary inversely with the absolute pressure while the density varies directly with the pressure." (20:97) In other words, if the pressure on a gas is doubled--which is what happens in a diver's lungs at 33 feet--the density also is doubled, but the volume is decreased to only one half the original volume.

In order further to consider Boyle's law as it applies to human beings, the physical make-up of man should be examined. Man's body is composed of "about" 70 percent water and 30 percent solid tissue, neither of which is compressible. The "about" in the previous sentence is what causes man all his trouble in being a part of the deep ocean. A man's body is not comprised totally of water and solid tissue. It also contains several air cavities--lungs, throat, sinuses, and middle ears.

According to Boyle's law, the amount of air in a diver's lungs is compressed to half its original volume at a depth of 33 feet. Hence, a diver would need to take in twice as much air in order to maintain his lungs at their normal size. Since there is almost a free passage of air from lungs to throat to sinuses, and middle ears, the air in these cavities is compressed simultaneously. The air inside the lungs and other air cavities increases in pressure as a diver goes deeper in order to equal the ambient pressure of the water. (20:103) Since a diver takes into his lungs twice as much air at a 33-foot depth as he does at sea level, it follows that at 66 feet he must take in three times the amount breathed at sea level; at 99 feet, four times, and so forth.

The body can withstand great pressures providing the pressure in the body's air spaces equals that of the surrounding water. The density of air in the diver's lungs must increase so that they will not become compressed. (16:102) This increased air pressure involves increases in the individual elements of the air as well, which can result in critical consequences to the diver.

Dalton's Law of Partial Pressures. Dalton's law states, "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." (20:117)

Since atmospheric pressure is 14.7 p.s.i., then 79 percent of this pressure, or 11.6 p.s.i., is attributed to nitrogen, while about 21 percent of atmospheric pressure, or 3.1 p.s.i., is due to oxygen. The components of pressure are known as partial pressures. As a diver descends and the pressure around him increases, the partial pressure of each of the components of the air he breathes also increases. At a depth of 33 feet, he breathes 23.2 p.s.i. of nitrogen and 6.2 p.s.i. of oxygen--double the amount breathed at the surface. As the partial pressures of the individual gases increase, more of the gases are absorbed by the liquids and tissues in contact with them. Under pressure, gases may have serious effects on a diver's body. Oxygen, for example, becomes lethal about 30 p.s.i. for most people. The negligible partial pressure of carbon dioxide in atmospheric air becomes more serious with depth. It is the increased partial pressure of nitrogen that causes compressed-air illness and nitrogen narcosis. (16:104) Moreover, when a diver breathes compressed air under the sea, Henry's law of gases comes into effect within his body.

Henry's Law of Gases. William Henry, an English chemist of the late eighteenth and early nineteenth century determined that "The amount of a gas that will dissolve in a liquid at a given temperature is almost directly proportional to the partial pressure of that gas." (20:121) In other words, when a mixture of gases is exposed to a liquid, each gas within the mixture will diffuse itself into the liquid until its partial pressure both within and without the liquid is equal.

The nitrogen in air tends to go into solution in a diver's blood stream and fatty tissue. The deeper he goes, the higher the pressures and the greater the diffusion of gas into his blood. (20:121) As the blood absorbs the excess gas which can be taken into solution as a result of the increased pressure, the tissues of the body absorb their share of the increment until, with the passage of time, they come to be in equilibrium with the gas content of the blood and the ambient atmosphere. Since the degree of tissue saturation varies with the duration of the dive, decompression requirements also vary according to the duration of the dive. (16:104)

If a diver remains under the greater pressure long enough, his blood gradually becomes more saturated with nitrogen at that pressure until equilibrium is reached. For example, if a diver is saturated with nitrogen at 132 feet, the total pressure of the nitrogen dissolved in his blood will be five atmospheres. If the diver is then brought quickly back to the sea-level atmosphere, it would be like uncapping a bottle of soda water. The partial pressure of the nitrogen in the diver's body is suddenly four atmospheres higher than the surrounding partial pressure of nitrogen in the air, and the excess air comes out of solution in the form of bubbles in the blood stream. If the diver is allowed to equalize with the decreased air pressure slowly, the excess air will gradually diffuse through the alveolar membrane in his lungs into the air, and no bubbles will form. (20:122)

It may be pointed out that air is not the only gas that can be breathed in a hydrostatic pressure environment. The ratios of nitrogen to oxygen can be changed in order to use the mixture best suited for a particular depth. The advantage of doing this does not seem to compensate for the trouble it takes. Oxygen poisoning could easily enter the picture here.

Oxygen poisoning becomes a diving hazard when the partial pressure of oxygen rises above that produced by pure oxygen at sea level--somewhere above one atmosphere. Oxygen intoxication mainly affects the brain, and can cause convulsions if allowed to go far enough. The minimum partial pressure of oxygen that can cause oxygen poisoning is not known, but it can definitely take place with an oxygen partial pressure of two atmospheres. A diver subjects himself to two atmospheres of oxygen by breathing 100 percent oxygen at 33 feet or 50 percent oxygen at 99 feet, or plain compressed air at around 280 feet. (33:71)

Experiments have been made to reduce some of the hazards of gas absorption to the diver. Helium has been used to replace the nitrogen in air with extremely gratifying results. Although extensive testing is still underway, the breathing of helium when mixed with the proper amount of oxygen has proved to be harmless. Oxygen and helium must be mixed in proper proportions to suit the depth of the particular dive involved. Oxygen concentration must be kept below two atmospheres pure oxygen. The absorption rate of helium is more rapid than that of nitrogen, and by the same token, elimination is also faster. Since helium dissolves more quickly than air in the blood and tissues, divers need more decompression time for short dives and less for prolonged dives.

Helium, of course, eliminates the danger of nitrogen narcosis. Its density seems to be the key to success for its underwater use. Divers are more mentally alert, and the sense of depth commonly experienced when breathing air is greatly reduced. Since the lungs get better ventilation, divers can work harder and longer. (33:84)

Divers say that helium takes no effort to breathe. However, it makes them feel very cold and changes their voices into high-pitched nasal whines. A team of physiologists explained the high pitch by the fact that a man pumps light helium past the vocal cords much faster than nitrogen, and helium does not resound as heavily as air in the sounding cavities around the larynx. (10:58)

More and more use of helium will be made in the future. It is the only gas, other than, possibly, hydrogen, that can be used successfully in the depths to which divers aspire.

CHAPTER III

DIVING HAZARDS AND DECOMPRESSION

In the discussion of physics and physiology, it was shown that as a diver descends, the state of the gases in his air spaces is governed by the ambient pressure of his environment. The deeper he goes, the more pressure is exerted on these gases; as the pressure increases the gases more readily enter his blood stream and tissues until after a period of time his body is saturated. If a diver ascends too rapidly and does not vent his lungs properly, grave consequences may result. Some hazards of descent to and ascent from the depths are hereinafter considered.

The diving hazards treated in this paper are only the worst of those physiological dangers that occur in deep-diving situations where the divers are breathing a gaseous mixture. The worst diving harards are air embolism, the bends, and nitrogen narcosis. Pressure squeeze is a great hazard to hard-hat divers and will also be treated here.

Air Embolism. Traumatic air embolism is one of the worst physiological hazards confronting a diver. It is caused by a build-up of excess pressure inside the lungs. This build-up is usually due to a willful or panic-driven neglect to vent the lungs of compressed air while ascending toward the lesser pressures at the surface. Neglect in venting the lungs may be due to an involuntary muscle spasm caused by aspirated water or vomiting. The diver who holds his breath in panic will surely die from air embolism in ascending, possibly from even the deep end of a swimming pool. Boyle's law explains why air embolism occurs. A diver breathing compressed air at a 33-foot depth is breathing twice the volume of air that he would at sea level, so there is twice as much air in his lungs. If he holds his breath and comes to the surface, the internal air pressure in his lungs is twice that of the external pressure, causing his lungs to rupture. Usually, in air embolism the air is forced through the lung alveoli into surrounding capillaries and thus into the blood stream. Any bubble too large to go through constrictions in arteries will form an obstruction as a blood clot (embolus), thus restricting the blood flow. This embolus frequently travels to the brain, and death or severe brain damage results. (20:107)

There are three other maladies that may result from failure to equalize pressures inside and outside the lungs during ascent. These are: (1) mediastinal emphysema, (2) subcutaneous emphysema, and (3) pneumothorax. Problems of ascent may also occasion the bends.

The Bends (Decompression Sickness). Decompression sickness is caused by nitrogen bubbles trapped in the body tissues or blood stream after rising too rapidly from a deep, prolonged dive. It is also known as compressed-air illness, caisson disease, and, the bends. Under pressure, nitrogen is dissolved in the diver's blood and carried to the tissues throughout his body. The tissues demand nitrogen until they become saturated. This is a slow process. The longer the dive, the more N_2 is absorbed. The process reverses as the diver ascends. Nitrogen returns to the blood, is carried to the lungs, diffuses into the lung air, and is eliminated upon exhalation. If the diver ascends too rapidly, the partial pressure of the dissolved nitrogen in his tissues and blood may become considerably greater than his surrounding pressure. Nitrogen bubbles form. These bubbles can become entrapped in the tissues, blood vessels, or bone joints. The degree of injury depends on the size of the bubbles and where they become lodged. If bubbles form in the brain, lungs, or spinal cord, decompression sickness can be fatal. In any other part of the body, the bubbles can cause great discomfort, which develops to unbearable pain. The symptoms range from itchy skin to stiff joints, partial or total paralysis, blindness, and convulsions. Most often bubbles lodge in the limb joints, causing the diver to contort himself from the pain--hence, the term "the bends." (16:127) The following hazards are encountered in descents rather than ascents.

Nitrogen Narcosis (Rapture of the Deep). Nitrogen narcosis is a kind of narcotic effect similar to drunkenness or anesthesia that seizes the diver as he descends. Some degree of nitrogen narcosis is probably detectable at every depth below the surface. Experiments by the U.S. Navy Experimental Diving Unit demonstrated a significant impairment of reasoning in 39 percent of highly trained personnel at the depth of 100 feet. Nitrogen narcosis seems to be a "drunkenness by degrees" which slows organized thinking and impairs movement. The exact cause of nitrogen narcosis is not known, just as it is not known how anesthesia is caused by the use of nitrous oxide and oxygen (laughing gas). (34:73)

Squeeze (Barotauma). Pressure squeeze is the opposite of air embolism and occurs during descent instead of during ascent. Again, according to Boyle's law, internal and external pressures always tend to equalize. If a rigid air space in the body is prevented from being equalized, pain and distortion of the affected area results. If a diver fails to equalize the pressure in his middle ear with the ambient water pressure, for example, his eardrum will be distorted by the excess water pressure until it finally bursts. (20:109) Squeeze is a hazard that always accompanies the hard-hat diver. If a hard-hat diver gets a hole in his helmet or an air hose breaks, the external pressure will tend to squeeze him into his helmet and out of the hole unless the pressure release is checked. Some horrifying examples of this phenomenon have occurred at great depths where pressure has turned murderous. So it is seen that the effects of pressure constitute the chief problems confronting divers. Among the most successful measures for countering these effects are in the field of surfacing with gradual decompression.

Decompression. In the discussion of diving hazards, it was shown what can happen when a diver ascends too rapidly and does not vent his lungs properly. The act of surfacing at a certain rate of time is called stage decompression. During decompression the gases reenter the blood stream and are expelled by diffusion through the alveolar membrane of the lungs. The rate and length of time for decompression depends on the amount of time and depth of the dive.

Decompression tables and procedures for surfacing from various depths have been developed to provide safety from the hazards of decompression sickness and oxygen toxicity. These tables and procedures are presented at length in the U.S. Navy Diving Manual. Tables listed are of three types--Standard Air Decompression, No Decompression plus Repetitive

Dives, and Helium-Oxygen Decompression. The table that applies to standard air decompression extends to 190 feet, which is considered the deepest safe working level using compressed air. The table that applies to helium-oxygen extends to 400 feet and can be interpreted to 600 feet.

Prompt recompression is the only treatment for air embolism and decompression sickness. There are only two ways to recompress a diver's body. One way is to lower the diver back into the water. This is a difficult maneuver with a diver who is dressed in a hard-hat diving rig; it is extremely difficult and dangerous even to attempt, with a diver using a self-contained apparatus. (33:178)

The solution to this formidable problem is a recompression chamber. The role of the recompression chamber is to simulate a desired pressure medium or depth. Pressure can be controlled in order to bring the diver, who is inside the chamber, back to a normal atmospheric pressure. There are two common types of recompression chambers. The principal one is a one-lock chamber having a working pressure of 100 p.s.i. The other is a two-lock chamber having a working pressure of 200 p.s.i. The principal advantage of a two-lock chamber is the ability of personnel to enter or leave during the course of treatment. This chamber has a total volume of about 500 cubic feet. The inner lock is the larger of the two, with a 370-cubic-foot volume. (33:178)

In using the recompression chamber, the diver and attendant occupy the large inner lock. When it is necessary for the attendant to leave the inner lock, pressure is built up in the outer lock so the door between the two locks can be opened. The attendant is then given proper decompression during ascent in the outer lock. All regular chambers are fitted with a medical lock for sending food, medical supplies, and other articles in and out.

Recompression chambers are not simple pieces of equipment. They need many controls, valves, and gauges, plus a proper supply of gases to insure the correct mix of air or other gases, such as helium, which are pumped inside. Explosive fire is the most serious danger in operation of a recompression chamber. The danger is increased as the pressure is increased and when pure oxygen enters the chamber. Every precaution is taken to reduce the fire hazard.

In conclusion, it can be stated that the condition and availability of recompression chambers is of paramount importance in combating the hazards of deep-diving.

CHAPTER IV

SATURATION DIVING

Quoted below is a paragraph from the 1963 U.S. Navy Diving Manual. "At present, helium-oxygen is confined mainly to surface-supplied diving with equipment specially designed for the purpose." (33:178) Even before this was written, the new concept of "saturation diving" that relies on the extensive use of helium was introduced into the science of diving.

Definition. In saturation diving (extended diving), the diver is exposed to pressures past the time at which complete saturation of blood and tissue by inert gases is assumed to have taken place. It is estimated that when a diver has been exposed to a specific pressure for 24 hours or longer, every tissue of his body will have absorbed at least 98.5 percent of all the inert gas that it is capable of absorbing. Decompression limits the time available for work in the traditional form of surface-based diving. For example, if a deep-sea diver were to spend 12 hours at a depth of 300 feet, he would be required to spend a minimum of 60 hours undergoing stage decompression. However, a diver exposed to this same depth within a framework of the saturation diving method for 24 hours, several weeks, or even several months, would be required to pay a decompression time penalty of only about 55 hours undergoing a constant rate of ascent type of decompression. (26:104)

Experiments. In 1957, Captain George Bond, Walter Mazzone, and Robert Workman introduced the concept of saturation diving to the Navy while stationed at the New London Naval Medical Research Laboratory. The initial project, a series of chamber experiments, demonstrated the ability of animals and man to exist for prolonged periods at high pressures breathing appropriate mixtures of helium, nitrogen, and oxygen. In adapting to this high pressure environment man is limited in his ability to quickly ascend to shallower water or to the surface. This limitation is more than compensated for by the increased ability to make deep excursions and by the extensive work periods available at the saturation depth. (6:45) Other Navy requirements postponed the continuation of work with humans during the late 1950's, which is probably why the above quotation was still in print in 1963. However, research and experimentation were pursued by certain interested civilians, among them Edwin A. Link, a retired industrialist, who in his deep-sea work has always cooperated closely with the Navy. Although the goals of the civilian in oceanology differ from those of the military, the methods of achievement run along similar lines.

In February 1962, Edwin Link described a Man-in-Sea project that had the ultimate aim of enabling men to live and work on the floor of the ocean at depths of 1,000 feet or more for days, weeks, and even months. The proposed program envisioned three major pieces of equipment besides the supply ship: an underwater pressure chamber affording house-like living conditions; a smaller one-man chamber which would act as an elevator between the bottom dwelling and the surface; and a large pressure-housing on the surface for comfortable decompression of several men at the same time. (22:715)

Seven months later, in September 1962, Robert Stenuit stayed at a depth of 200 feet for 25 hours, using a Link one-man chamber supplied with a helium-oxygen mixture. A Navy physician assisted in assuring the proper mixture of gases and in keeping strict medical surveillance on Stenuit. (22:713)

Underwater work was progressing surely but slowly. Then a tragedy occurred that shocked the world. The USS "Thresher" sank in 8,400 feet of water 260 miles off the New England coast on 10 April 1963. For the first time since the last submarine tragedy, the shortcomings of United States naval underwater technology were borne out. The Navy had long been aware of the gap between the operational capability of its ships and its understanding of the deep-ocean environment. The loss of the "Thresher" showed again that rescue and salvage techniques were far below requirements for deep-water work.

Deep Submergence Systems Review Group. The Deep Submergence Systems Review Group (DSSRG) was established to analyze existing Navy techniques relating to undersea operations and to formulate specific requirements for improved systems. In 1964, the Deep Submergence Systems Project (DSSP) was created to implement the recommendations of the DSSRG. (5:24)

The Deep Submergence Systems Project is a far-reaching program directed toward a better understanding of the ocean environment. At the core of DSSP is the subject of submarine escape, rescue, and salvage. It has a fourfold goal: (1) by 1970, rescue of personnel from stricken submarines in water depths well below 3,500 feet--a depth that will gradually be extended; (2) salvaging of large objects the size of a submarine or a destroyer in water depths of 600 feet or more; (3) perfecting the equipment and techniques that will allow men to live and work on the ocean floor at 600 to 1,000 foot water depths for several months; and (4) development of a deep-diving vessel that will allow men to search and recover small objects down to 20,000-foot depths. (12:4)

"Man-in-the-Sea" Program. All four of these goals are tremendously interesting and challenging. The interest of this paper bears directly on the third goal which is embraced in the "Man-in-the-Sea" program.

> The Navy has recommended to the Defense Department a rapid expansion of ocean research that could amount to one billion a year by 1970. This includes a new program of 'deep technology' that is larger than the present 'deep submergence' project, which will expand. The Navy projects are under the direction of Rear Admiral Odale D. Waters Jr., who has been given the newly created title and additional authority as Commander of the U.S. Naval Oceanographic Office.
>
> Referring to the Navy's man-in-the-sea program, Admiral Waters predicted that in 10 years, 'we will have colonies of aquanauts living and working at any place they choose on the continental shelf and at depths in the neighborhood of 1500 feet.' (32:8:3)

The basic concept of this program is to furnish a suitable habitat for men on the ocean floor, allowing them to work on the sea bed for long periods without returning to the surface, thus minimizing the frequent long, nonproductive periods of decompression associated with conventional deep-diving operations.

Sealab I and II. The first of the actual underwater vehicles was Sealab I. It was lowered to the ocean floor in 192-feet deep water off Argus Island, the Navy's oceanographic research tower, in 1964. Four men remained for a period of ten days in Sealab I and were carefully monitored during and after the experiment for evidence of significant physiological effects. Through this experiment it was demonstrated that men could dive in an artificial helium-oxygen atmosphere, at a depth of 192 feet, for at least an 11-day period and not experience any harmful effects. (15:66)

Sealab II was constructed at the San Francisco Naval Shipyard. The completed habitat had living space for ten men. The pressurized personnel transfer capsule was developed to transport the aquanauts from the bottom to the surface, where they were transferred to a larger and more comfortable decompression chamber. When not in use, the personnel transfer capsule rested alongside the habitat providing a refuge in case the Sealab had to be evacuated. Sealab II was placed on the bottom of the ocean in 205 feet of water in the fall of 1965 off the coast of La Jolla, California where it remained for 45 days. Twenty-eight men, working in three teams, lived and worked on the ocean bottom for 14-day periods, with two of the aquanauts remaining down for a total of 30 days. The rigidly controlled atmosphere in Sealab II consisted of a mixture of about 4.3 percent oxygen, 18 percent nitrogen, and 77.7 percent helium. This ratio was maintained at the pressure of seven atmospheres. Lithium hydroxide was used as an absorbent to remove carbon dioxide from the atmosphere. (2:109)

Sealab II extended the physiological and psychological testing program that was begun during Sealab I. Diving equipment was evaluated, as were performance capabilities in carrying out salvage and work details. (6:45) Normal values of physiologic processes of man under hyperbaric, synthetic atmosphere conditions are not established yet. The test data obtained from Sealab II indicated that no major physiologic changes occurred in the aquanauts. (26:106)

Modifications are now being made to the Sealab II habitat. It will be put back on the ocean floor as Sealab III probably not earlier than November of 1967, at a depth of 500 feet, to extend man's underwater capability. By 1968, the Navy hopes to have a 40-man experimental colony of aquanauts living in a large ocean-bottom structure to be known as SEAHAB, 600 feet or more below the surface. (12:4)

Conclusions. It appears that a more thorough use of saturation diving is forthcoming. There are advantages and disadvantages in the use of this type of diving. The one great advantage is that the diver may spend almost unlimited time on the bottom. For the price of one round trip through the air-water interface he may stay long enough to accomplish what hundreds of ordinary dives might not accomplish. He needs to decompress only once instead of many times.

On the other hand, saturation diving is extremely hazardous. The diver in his deep-water environment has no counterpart of the parachute. If he gets lost, or if his equipment malfunctions, he cannot come directly to the surface and remain alive. It makes little difference whether his body tissues are saturated with dissolved gases at the pressures of 70 feet or 700 feet. The excess dissolved gases must come out of solution virtually a molecule at a time.

There is little point in braving dangers of extended diving if underwater tasks can be accomplished in another manner. Tasks requiring underwater time of short duration and in depths of 200 feet can be accomplished with moderate ease using scuba or hard-hat diving methods. Saturation diving is a tool for deeper water.

CHAPTER V

FUTURE ROLE OF DEEP DIVING

The program envisioned by the U.S. Navy considers not only far-reaching results, but also immediate use of man in a deep-water environment. It is a scientific program that promises great returns but that still faces a wide range of problems.

Current Problems. The problems concerning men and equipment at great depths are many and varied. In underwater habitats such as the Sealabs, where a breathing medium of helium-oxygen is provided for the aquanauts, standard equipment becomes permeated with the helium. It seeps through glass to fog TV cameras and does other strange things. (12:7) There have also been problems in communications, thermal protection, and navigation that have hindered the aquanauts in carrying out their projected missions.

Chief among the hazards to divers is pressure and its effects. At a depth of 600 feet it is dark and cold, and the pressure is tremendous. Because of the density problem it is difficult to move gas in the lungs--even a gas as light as helium. The Navy will probably choose hydrogen, the only gas lighter than helium, for increased depths. The danger of inflammability of hydrogen at depth is slight, since the percentage of oxygen will be low. (7:44)

Psychologically, man seems to be able to withstand all the strains put upon him. Much of what can be done in the depths is dependent upon the ability of man to live there for long periods, leaving his pressurized vehicle or undersea home to perform useful work. Realization of this concept is close at hand.

The Future. Advancement in underwater scientific technology insists that man does not forget his lessons of the past. The process of attaining the depths has been one that has stretched over a period of at least 6,500 years. The future effects of a developing technology which permits occupation and habitation of the deep ocean are limited only by man's imagination. The expected yields from the oceans are staggering.

When man can work on the continental shelf, which is approximately 600 feet deep, he will possess the key to more than 10,000,000 square miles of sea bed. (24:801) He will uncover the scientific secrets of the ocean floor. He will be able to harvest the animal, vegetable, and mineral wealth of the vast areas of the continental shelf. Exploring ancient wrecks, mining diamonds or gold, working at the base of ocean oil rigs, farming the sea floor, and herding fish like cattle are a few of the tasks that might bring a great return of investment. Along with the resource potential, there will be a definite scenic and recreational potential.

The tasks listed above are nonmilitary in interest. At least they sound that way. Rear Admiral O.D. Waters, Jr., recently stated:

> I predict that by 1975 a great deal of our oceanographic survey work, including such areas as water temperature, current patterns, shore erosion, ice movements, and the like may be done by satellite, or with at least satellite assistance. My office is directing already a sizeable study on this project.
>
> I predict that by 1975 submarines will be capable of operating routinely at 20,000 feet.
>
> I predict that by 1976 we will have colonies of aquanauts living and working at any place they choose on the continental shelf and at depths in the neighborhood of 1500 feet.
>
> And I predict that by 1975 we will have made big strides toward solving the fresh water problem and that there will be a possibility of bringing blossoms to desert areas. (12:5)

Those predictions do not sound altogether military in scope. They might be encompassed in a proud slogan of the U.S. Navy--"The Navy Leads in War and Peace."

What are some of the advantages of underwater technology to the United States national security? The military significance of the continental shelf and the use or control of these depths have not as yet been fully assessed, but certain advanced capabilities and potentials are obvious.

Frogmen of World War II and Korea did an outstanding job in clearing underwater obstructions and in accomplishing many other military missions. The ability to accomplish missions of this same type will remain important in the future.

Salvage and rescue techniques have changed very little over the years until quite recently. Techniques now considered impossible could become, if not commonplace, at least attainable, in the near future.

Underwater construction, repair of submarine hulls, salvage of sunken ships and airplanes, rescue of personnel, collection of oceanographic data, and direct observation of biological and physical phenomena are all subjects for investigation by extended deep diving. It is not implied that man working with his own muscles and hand tools is the most important part of operations at continental shelf depth, but it is emphatically implied that man has an important role in these projected operations.

Conclusions. The machine has yet to be invented that equals all the underwater abilities of man. Until such a mechanical device exists, there will be a use for man underseas. In the underwater environment, the work can be performed best when man can apply his hands and hand tools directly to the task.

Of great value in the performance of these tasks is the development of the technological capability to utilize divers at depths greater than 200 feet for an unlimited amount of time. This has important potential value to the U.S. Navy. Manned undersea bases for weapons systems and surveillance can be envisioned in exploiting this technological capability.

Since man's limitations, to date, have not been adequately researched, and it is not now possible to estimate an ultimate deep-water working depth, the predictions of Rear Admiral Waters regarding the spectacular underwater advances do seem entirely plausible.

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