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REPORT

ON USE OF

HELIUM OXYGEN MIXTURES

FOR DIVING

EXPERIMENTAL DIVING UNIT
NAVY YARD, WASHINGTON, D.C.
APRIL 1939

Revised October 1942

UNITED STATES NAVY YARD
WASHINGTON, D.C.

21 MARCH 1939

From: The Commandant.
To : The Chief of the Bureau of Construction & Repair.

Subject: Helium-Oxygen Mixtures for Diving - Report on.

Enclosure:
(A) General Discussion of the Development of the Project.
(B) Example of Computation of a Decompression Table for use with Helium-Oxygen Diving.
(C) Helium Decompression Tables up to 450 Feet.
(D) Instructions for Mixing Helium and Oxygen for use in Diving.
(E) Instructions for Using Helium-Oxygen Gas Mixtures for Diving.
(F) Influence of Exercise on Decompression Requirements.
(G) Article entitled "The Treatment of Compressed Air Illness Utilizing Oxygen."
(H) Article entitled "Respiratory Resistance, Oil-Water Solubility, and Mental Effects of Argon, Compared with Helium and Nitrogen."

1. During the period 1 September 1937 to 1 April 1939, experiments have been conducted in the Experimental Diving Unit substituting helium oxygen mixtures for air in respiration of deep sea divers. The results of these experiments are described in the enclosed report, and have been obtained in conjunction with nearly seven hundred dives. A summary of the conclusions reached are as follows:

(a) Mental reactions. The sense of depth commonly experienced when exposed to high pressure when breathing air is very much reduced. At a depth of 500 feet the diver's head is clear and he feels no deeper than about 100 feet.

(b) Physical reactions. Divers can work considerably harder and for longer periods when breathing helium-oxygen mixtures than when breathing air, because of the increased efficiency of ventilation and consequent improved oxygen supply to and carbon dioxide removal from the blood.

(c) Reduction in decompression time is possible for the reasons that the water fat solubility ratio of helium is considerably less as compared to nitrogen, and that when using synthetic gases advantage can be taken of increased oxygen per cent during decompression.

UNITED STATES NAVY YARD,
WASHINGTON, D.C.

21 March 1939

Subject: Helium-Oxygen Mixtures for Diving - Report on.

(d) The characteristics of the helium-oxygen decompression table are different from nitrogen tables because a larger volume of gas is concentrated in the faster desaturating part of the body and the rapid diffusion of gas from one part of the body to another requires the keeping of the body at higher pressures for a longer period during the primary period of the decompression.

(e) It is necessary to supply heat to the divers in water temperatures less than 60°F because of the rapid heat loss through the helium gas.

(f) When using helium oxygen mixtures for diving several changes in the diving dress are necessary. First, a recirculating system must be provided in order to conserve gas. Second, a more efficient means of attaching the breast plate to the suit is essential for handling the diver in the submerged chamber and third, an auxiliary canister for removal of carbon dioxide must be provided in the helmet because of the extreme importance of keeping the helmet free of this dangerous gas.

2. This report includes the above listed enclosures.

3. Without the excellent cooperation and unyielding perseverance on the part of all personnel attached to the Experimental Diving Unit, this most intricate problem could never have been projected to the point that it has.

4. It is recommended that one vessel of the Navy be equipped for helium-oxygen diving in order that the practical application of helium-oxygen gas to diving may be studied under sea going conditions. It is believed that some of the personnel of the Experimental Diving Unit should be sent to this ship in order to utilize their experience in this field.

GEO. PETTENGILL.

Copy to:

OpNav
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BuM&S

GENERAL DISCUSSION OF THE DEVELOPMENT OF THE PROJECT

Lieutenant Commander C. B. Momsen, USN.

The diving suit of the present day is essentially the same as the one that Siebe, an Englishman invented in 1837. It is a closed dress made of heavy water proof canvas. This is attached to a breast plate which is a saddle shaped metal plate which fits around the neck and rests on the shoulders. The helmet is attached to the breast plate by an interrupted screw thread. Air supply hose and telephone cable and life line combined are attached to the helmet, being passed around under the left arm so that the left hand can manipulate the air supply through the control valve. On the helmet at the point where the supply air enters, an automatic non-return valve is installed so that if the air hose is ruptured air will not escape from the helmet. On the right side of the helmet an exhaust valve is provided. This has a spring loaded valve in it, the action of which is to allow the pressure in the helmet to be slightly greater than the surrounding water pressure so as to keep the suit partially inflated and thus keep the weight of the helmet and breast plate off of the diver's body. The exhaust valve opening can be adjusted for the amount of air that is desired to have excape in order to insure proper ventilation. About 41/2 cubic feet of air per minute per atmosphere is considered sufficient for working conditions. The main purpose of having this ventilation is to keep the carbon dioxide and moisture content in the helmet at a low level. While it is also essential to provide make up oxygen, this can be accomplished with a very much smaller supply.

While some divers do not use gloves, it is the usual practice in the U.S. Navy to have canvas gloves cemented to the sleeves. These gloves are a split mitten, two fingers in each partition. A heavy leather belt with lead weights fastened to it is placed around the waist outside of the suit. There are straps over each shoulder to take the weight and a jock strap through the crotch to hold the suit down and close to the body. The legs are tightly laced so that they will not fill with air and upset the distribution of buoyancy. On the feet heavy lead soled shoes are worn. The entire equipment weighs about two hundred pounds.

From the earliest days of diving, man has dreaded the disease of divers known as bends. History is filled with cases where men have come up from the depths paralyzed, blind, cramped with pain, or even totally unconscious. For years they did not understand the reasons for bends. They prayed for relief, took hot baths, and even partook of magic in one form or another. The problem has been studied by many prominent physicians and physiologists. The application of the laws of physics and the method of trial and error have gone a long way toward the solution.

Haldane, a prominent English physiologist, in association with Boycott and Damant, made the greatest contribution to the art of diving when he introduced the stage method of decompressing after a dive. It was he, too, who classified the various tissues of the body according to the time that it takes the blood stream to fill them with gas. He published tables up to a depth of 204 feet which were generally safe. These tables have been extended by others, but since Haldane did not publish his exact method of calculating his tables, the extension has been made the hard way, e.g., by trial and error.

Nitrogen is a very stubborn gas with a great affinity for fat and a hundred successful dives might be made using the same decompression table without the slightest symptom and yet the one hundred and first dive on the same schedule may develop a serious case of bends.

Experts have been casting curious eyes in the direction of helium as a substitute for this nitrogen for years, in fact ever since it was first suggested by (Sayers, Hildebrant and Yant) in 1921.

The U. S. Navy took steps to investigate Helium, starting in 1925. It was found that mixed with the proper amounts of oxygen it was absolutely harmless at atmospheric pressures and that under pressure it seemed to be better than air. They found also, that a diver can get bends from helium just as badly if not worse than from air. The studies were interrupted for a number of reasons and the problem lay more or less dormant until 1937. In the past year considerable progress has been made. Divers have reached a depth of 500 feet in tanks and 400 feet in the open sea. Promise of even greater depths has been indicated.

Older divers and pioneers in the diving art simply cannot believe that such depths are within the grasp of man. The unravelling of the mysteries of the theory of decompression from a helium dive has been quite complicated and at time disappointing, but at no time without interest. New equipment must, of course, go hand in hand with the development of the theory. Both have led the investigators up many blind alleys.

For instance, it was found that a man suffers more from cold when breathing helium than when breathing air. Electrically heated under clothing was provided and it was found that about twice the heat was required to keep a diver warm in cold water when breathing helium as compared with when breathing air. Temperatures at great depths in the sea are very low, in fact they may be well below freezing.

Substances which are not ordinarily combustible under atmospheric conditions might become highly combustible when exposed to high oxygen. Consequently the ordinary insulation of diving underwear which might be considered safe in every-day life would become dangerous to a diver when he is exposed to high oxygen pressures. To meet this condition steps have been taken to have the wires used in the heating elements in the diving underwear insulated with glass thread and the wire pads enclosed with glass cloth.

Another problem which develops when divers go to great depths is the matter of handling his hose, life line and telephone cable. Aslight current on a long scope of these lines might very well pull the diver off of his descending line.

Stronger hoses and fittings than heretofore used have to be developed. Several changes in the standard diving dress have had to be made.

To use synthetic mixtures at the rate of 4 1/2 cubic feet per atmosphere, per minute, would require very large storages of gas aboard ship. In order to reduce the amount used in the suit, it was necessary to develop an apparatus that would first, remove the excess carbon dioxide, second, remove the excess moisture and third, provide make up oxygen for that consumed by the body. The first consideration was the oxygen, for in addition to making certain that the diver has enough oxygen to sustain life, it was highly desirable to keep up the oxygen partial pressure so as to prevent the increase of partial pressure of the helium that controls the decompression requirements. It was calculated that a half a cubic foot (14 liters) of gas containing not less than 15% oxygen would provide about 2.1 liters of make up oxygen per minute, which is enough to sustain life in a man doing fairly hard work. A closed circuit which would return the exhaust gas to the surface for revitilization would be impracticable. It was first thought that it would be necessary to provide the diver with supplementary equipment somewhat resembling the rescue breathing apparatus, including a compressed supply of oxygen-helium mixture. This idea was, however, abandoned. The gas contained in the diver's dress must be revitalized by forcing it through a chemical absorbent. In the rescue breathing apparatus a mouthpiece is employed whereby the lung pressure is used to accomplish the circulation. In order to avoid the use of a mouthpiece and yet maintain a forced circulation it was suggested by the late Dr. J. A. Hawkins of the Experimental Diving Unit that the oxygen-helium supply which provides the make up oxygen to be used as a driving agent in an aspirator to force the diver's gas through the absorbent without effort or attention on his part.

It has been found that the standard hose and fittings should be retained. A small hose is led from the regular hose on the supply source or surface side of the control valve. With this arrangement the driving gas is led to the jet described below, with the control valve closed, yet should the diver require a sudden additional supply of gas, as for instance when descending, he has merely to open his control valve.

The aspirator, or circulator as it is called by the divers, is a venturi tube, into the throat of which a jet is fitted, having an orifice so proportioned that with 50 pounds per square inch differential pressure, a volume of gas, which contains oxygen, is introduced in any given time, which is sufficient to replace the oxygen consumed by respiration and, at the same time, the venturi tube forces a total volume from the helmet through a cannister containing moisture and CO_2 absorbent, and back into the helmet, which is equal to the volume exhaled by the diver in the same time interval. The excess gas that tends to accumulate escapes through the exhaust valve. By means of this circulator, the diver is given sufficient ventilation and uses only about one fifth the amount of gas that would be required using normal ventilation.

In the beginning of the work, soda lime was used as the absorbent, but it was found that it did not absorb the moisture and the excess moisture not only fogged the face plates of the helmet, but dampened the soda lime which reduced the effectiveness, allowing the carbon dioxide to build up.

Shell Natron, a caustic potash mixture, is now used and is quite satisfactory. It has a tremendous affinity for moisture and even when exposed to the air will deteriorate rapidly for this reason. This chemical was at first purchased in 50 pound drums, but it was found that in opening the drum from day to day, moist air entered the drum with the result that the last part of the material was spoiled. It is now supplied in three pound cartons and one pounds is used in the cannister for each dive. One pound has been found to last three hours provided the diver does no hard work, and 30 minutes doing hard work.

The method of attaching the breast plate to the suit of standard dress is accomplished by bolting. Twelve equally spaced holes moulded in the rubber collar of the suit fit over twelve studs in the breast plate. Four strips of metal, two in front and two behind, fit over the studs to hold the collar securely. Wing nuts clamp the strips into place.

While the standard method of attaching the breast plate to the dress is satisfactory when diving on air, it has undesirable features when using helium-oxygen mixtures. In the first place the old attachment is not always gas tight and it is more important to keep the suit tight when using helium because a small amount of gas is used. In the second place, it is desirable to have the suit so built that the diver can be quickly undressed by one man for reasons that will be explained elsewhere. A mean of attaching the breast plate to the suit by quick operating wire cables invented by Mr. William Scrimgeour, was developed by the Navy Yard, Washington, D.C. and suits without the moulded holes in the rubber collars were obtained. The new method of attachment makes the suit tight and does not detract from the comfort of the diver. By suspending the weight of the helmet and breast plate from overhead one man may remove them as a single unit from the diver quite easily.

When decompressing a diver after an exposure to helium-oxygen mixtures many hours time can be saved by using oxygen instead of continuing on the same helium-oxygen mixtures. It is however, feasible to decompress on air or on the helium-oxygen mixtures. It was found that the body cannot stand a direct change from helium to nitrogen at depths beyond six atmospheres without discomfort. The adverse effects may be caused by the sudden increase of weight of the nitrogen, because nitrogen is seven times the weight of helium. If, however, the air is supplied gradually, at the approximate rate of 3% increase per minute, the diver is unaffected, except for the usual sense of depth caused by the nitrogen. In actual practice gradual shift from helium to air is accomplished through use of the circulator for the first 20 minutes decompression time. After this air may be ventilated through the helmet in the usual manner. Using air for decompression is more economical than using oxygen or helium-oxygen. It is much slower and not as reliable as oxygen. Since pure oxygen should not be used at depths greater than 60 feet, the decompression must be made on helium-oxygen mixtures up to that point. It is desirable when doing this to keep the oxygen tension as near to 2 5 atmospheres effective as practicable.

It is not desirable to have the diver suspended over the side of the ship for long periods waiting for decompression. In the first place it entails more lines in the water and more tenders on deck, thus adding confusion to a job when it is desired to have work on the bottom proceed by using relief divers, in the second place it is uncomfortable for the diver, and finally it places the ship and the diver in a precarious position should it become necessary to move because of stress of weather.

For these reasons a submersible decompression chamber has been built somewhat similar to the rescue chamber which has been in use for many years. This chamber, containing one operator, is lowered in the water, being guided down the descending line by a large ring bolt welded to its side. A telephone and other essential equipment are inside. Upon reaching the depth of the diver's first stop, the pressure in the chamber is built up to an amount equal to surrounding sea pressure by admitting compressed air. The hatch at the bottom is opened and the descending line is fished into the hatch opening. The diver coming up enters the hatch opening by ascending a ladder attached to the bottom of the chamber. The operator passes a safety line around the diver, fastens another line to the helmet and then unfastens the breastplate wire. This permits the diver to duck out of his helmet and breast plate. The diver then puts on a breathing mask and decompression begins. The operator, after covering the breast plate with a canvas cover drops the entire apparatus out of the bottom of the chamber so that it can be hauled to the surface. He then closes the hatch and undresses the diver as necessary. The chamber can now be hoisted clear of the water and placed out of the way on deck. Decompression is controlled from this point on by the operator by means of regulating the air pressure inside the chamber.

It is contemplated having a means of locking the diver and operator from the submersible chamber to the main decompression chamber so as to render the submersible chamber available for the next diver.

When a diver is exposed to an increased pressure and is breathing air, the pressure is immediately transmitted throughout the entire body. Since the body is largely liquid and is for all practical consideration incompressible there is no sense of pressure as a physical force, except in certain small passages. The eustachian tubes and sinus canals are such small air passages which might be blocked by slight infection or by mucous. When this occurs the pressure tending to collapse these spaces may produce pain.

The body of a normal healthy man, such as a diver has to be, consists of about 80% water, about 15% fat, and the rest solids. It is a well known fact that fat and water will hold in solution definite amounts of gas. The amounts vary with the solubilities of the different gases and also vary directly as the pressure to which the liquids are exposed. While the amounts do also vary with temperature changes, the body's temperature is nearly constant and need not be considered.

Consequently when the body is exposed to increased pressures these physical laws cause the body liquids to have a greater absorption capacity for the gases. The process of increasing the saturation of the body is accomplished in the main through the blood stream. The increased pressure is first introduced into the lungs by breathing. The blood is distributed through tiny vessels, capillaries, over a tremendous area, approximately 1000 square feet, in the many folds and irregular surfaces in the lungs. These small vessels have very thin walls and the gases taken into the lungs diffuse through the walls into the blood. The capillaries flow into a larger vessel and the blood is assembled into a large artery where it starts on its journey through the body. When it leaves the lungs it is saturated with the gases which were present in the lungs to an amount corresponding to the solubilities of the various gases, the percentages of each gas present and the pressure to which the gases are exposed. The term partial pressure is used so much and can be so confusing that a definition of its meaning is in order. The partial pressure of a gas is the actual pressure multiplied by its percent of the total. Thus if air is 79% nitrogen, at a pressure of 100 pounds the partial pressure of nitrogen would be 79 pounds. It is customary to express the partial pressure (pp) in terms of feet depth of salt water when using the term in diving. An atmosphere of pressure (14.7 pounds per square inch) is very close to the pressure exerted by a column of sea water 33 feet high. Thus for rough calculating it is a close approximation to assume that each hundred feet of salt water will result in 3 atmospheres of excess pressure. To return to the blood stream which is saturated with gases from the lungs, the circulatory system now distributes the blood to every part of the body and when the blood is again spread out by means of capillaries these gases are exposed to the tissues and the partial pressure of gas builds up in the tissues while the partial pressure in the blood is lowered a corresponding amount. Of course, one of the main purposes of the blood circulation system is to supply the oxygen to and remove the carbon dioxide from the tissues. When the blood leaves the capillaries the gas pressure in the blood of each capillary is in a state of equilibrium with the tissues which it supplied. The blood is collected in veins and finally returns to the lungs. When the blood is returned to the lungs it has lost some of its partial pressure as a result of its distribution throughout the body and a new load of gas is picked up in the lungs. This process is continuous and when all of the tissues are saturated with the gases which are being breathed, the body is said to be in a state of saturation corresponding to this pressure. With every change in barometer and every change in altitude a readjustment of the amount of gas in the body follows.

An average persons' body contains about one liter of nitrogen in solution. This amount increases if the barometer increases and of course, decreases when it is lowered. The ability of the body to thus accommodate itself to changes of pressure causes the complicated problems of deep sea diving, for when a man has become saturated with gas at a great pressure, the process of elimination of this gas is slow and the lowering of the pressure must be slow so as to prevent the gas from forming as bubbles before the blood stream can carry it off through the lungs. It is hardly necessary to say that the formation of gas bubbles in the blood stream might be extremely dangerous if not fatal, for this condition is bends.

Gingerale is prepared with carbon dioxide gas in solution at a pressure of a few pounds more than atmospheric pressure. It has this gas in solution and the gas is, therefore, not visible. If, however, the bottle is uncapped the excess pressure is imediately removed and the liquid cannot hold as much gas in solution. Bubbles form and the gas escapes. (If the bottle were opened very slowly no bubbles would excape into the air). After several hours the gingerale would cease to bubble, that is to say the partial pressure of the gas in the liquid would be in equilibrium with the surrounding atmosphere and no more gas will come off. Liquids will hold a greater amount of gas than the solubility laws permit, without bubbling. The excess will begin to diffuse out, however, when a small pressure decrease is made. When a liquid contains in solution an excess of gas and yet this amount is insufficient to cause it to bubble it is considered to be super-saturated. This condition is utilized in providing decompression for divers.

To return to the example of the gingerale. If the bottle is uncapped and allowed to stand the bubbles will form and escape. At the moment that bubbles cease to come off the gingerale is super-saturated to its maximum. That it is super-saturated may be demonstrated by stirring the gingerale or shaking the bottle. The gas in super-saturation being in an unstable condition will again start to bubble. If the gingerale is super-saturated and the bottle is re-capped, the pressure will build up above the fluid in the bottle to an amount equal to the super-saturation pressure.

It has been found that the pressure on the body of a diver may be reduced a certain percentage of the total without causing bubbles to form. The relation of the total partial pressures of the gases in the body to the pressure to which it can be reduced with safety is called the safe ascent ratio. It naturally follows that the greater this ratio the more rapid will be the elimination of excess gas from the tissues.

When a man takes a breath of ordinary air it contains about 78% nitrogen, about 20.9% oxygen, .03% carbon-dioxide, various amounts of water vapor, .94% argon and minute quantities of the several rare gases. All of these are nearly constant except the water vapor and when the air is adjusted to the body temperatures in the lungs the water vapor percentage is constant and corresponds to the vapor pressure at 98.6°F. It is usually expressed as 47 millimeters of mercury partial pressure and in a standard atmosphere of 760 millimeters of mercury will be 47/760 or 6.2% of the total. This 6.2% of water vapor reduces the effective percentages of the gases breathed. Thus dry air contains about 79% nitrogen but after it enters the lungs it is reduced to about 79 over 106.2 x 100, or to about 74%. In the lungs the carbon dioxide which is being deposited by the blood is about 5.3%. As breathing proceeds fresh air is taken into the lungs and is mixed with the air in the lungs. Upon exhalation the mixture is released and this will contain somewhat less than 5.3% carbon dioxide. With each breath the carbon dioxide is washed out of the lungs so that the amount left is always about 40 mm partial pressure. Through automatic features in what is called the respiratory center through which the blood flows the depth of the breath and the number of breaths per minute are regulated so as to maintain the partial pressure of the CO_2 in the blood and the partial pressure in the lungs nearly constant.

Should the body be exposed to two atmospheres of external pressure, that is, one atmosphere excess, the partial pressure of both water vapor and carbon dioxide would remain the same but the actual percentage of the gas present would be halved. The importance of this fact may be seen when we consider breathing mixtures of gases which contain carbon dioxide. For instance, if air containing 4% CO_2 were breathed at atmospheric pressure it is easy to see that a great increase in lung ventilation is necessary in order to keep the CO_2 in the lungs at 5.3%. Also, if we breathe air containing more than 5% CO_2 we would soon find that no amount of ventilation would keep the lung CO_2 down to 5.3% and this would result in severe panting followed by collapse.

Likewise at two atmospheres absolute pressure if we breathe more than 3% CO_2 in air we would encounter distress. Thus if a man is breathing air in a confined space at one atmosphere and the CO_2 builds up to one or two per cent he may not notice the change in breathing. If however, this space were suddenly compressed to several atmospheres as in the case of a submarine compartment when flooding for excape, or in a diving bell when lowering in the water, the CO_2 effect would increase in direct proportion to the increased pressure and the same percentage that was hardly noticeable before would now become intolerable.

To much emphasis cannot be placed upon the importance of keeping the gases breathed free from CO_2 when working at higher pressures.

Every one is familiar with the fact that we breathe air in order to obtain oxygen which in turn supports life. While oxygen is no exception to the gas laws, its action in the blood is somewhat different from the other gases. It does go into solution in the blood much the same as does nitrogen, but almost immediately thereafter it combines loosely with the blood haemoglobin in a chemical combination and leaves but a small amount remaining in physical solution. It is chemically combined oxygen which supplies the tissues and for all practical purposes we do not have to consider oxygen as a gas in solution, even though it does exert its influence upon the percentage of the other gases, that actually enter into solution in the lungs. In effect this action of the oxygen produces a partial pressure vacancy. This vacancy must be filled by the other gases present when going from higher pressure to a lower pressure before a state of super-saturation can exist.

For example, consider the body exposed to two atmospheres, pressure 66 feet absolute and the gas breathed to be air. Suppose the nitrogen partial pressure is 79% x 66 or 52 feet absolute. Neglecting the influence of the other gases which will be discussed later and considering only the partial pressure vacancy created by the oxygen action we should be able to drop the pressure to 52 feet absolute without incurring any super-saturation on the part of nitrogen. We know that in addition to the drop in pressure that we can tolerate a certain amount of drop by reason of super-saturation. The degree of super-saturation that the tissues in the body can stand has been determined experimentally and is expressed as the ratio of the partial pressure to the absolute pressure of the depth. This ratio is about 1.7 to 1.0. In the case discussed above if the body is saturated at two atmospheres and the partial pressure of the nitrogen is 52 feet the pressure may be dropped by reason of taking advantage of super-saturation to a point obtained by dividing 52 by 1.7 which is 30.5 feet absolute.

Since 33 feet absolute is atmospheric pressure it would be safe to surface after saturation at 2 atmospheres or 33 feet gauge. Again suppose a diver remains at 100 feet gauge long enough to become fully saturated. This would be 133 feet absolute and by the same calculations he would have a nitrogen partial pressure of 79 x 133 or 105 feet. The absolute depth of the point at which he would have to stop would be 105 feet absolute divided by 1.7 or 62 feet absolute which would be 62 minus 33 equals 29 feet gauge.

Haldane, in his studies of pressure problems, inferred that all parts of the body do not saturate at the same rate because of different rate of blood supply and because of differenct capacities of the different types of tissues. His conception of time tissues are classified in accordance with the time that it takes them to become fully saturated. The process of saturation, as explained earlier is one of continuous equalization between the blood stream and the tissues. The curve formed by plotting per cent saturation against time is exponential in form and the values have been computed and made up into a table for convenient use. Figure 1. The designation given to a tissue is that time, expressed in minutes which it takes the tissue to half saturate. Thus a 20 minute tissue is one which will become 50% saturated in 20 minutes, 75% saturated in 40 minutes, 871/2% saturated in 60 minutes and half of each remaining amount for each additional 20 minute period, or for each additional time unit.

Of course, there are a great number of different time tissues and the tissues belonging to each are widely scattered. For convenience Haldane selected certain times for classifying the tissues. These are 5,10,20,40 and 75 minute tissues.

The writer prefers to plot all tissues in a continuous curve so as to obtain a clearer view of the state of saturation at each stage of the exposure to pressure. Such a series of curves which represent the saturation and desaturation of the body is given in Figure 2. While this hypothesis has been satisfactory in its application to diving on air, the use of helium as a substitute for nitrogen as a diluent of oxygen in breathing mixtures, has led to the belief that diffusion from one tissue to another, especially in the faster tissues has considerable influence on gas elimination. Lieut. A. R. Behnke, Medical Corps, U. S. Navy, a member of the staff of the Experimental Diving Unit, Navy Yard, Washington, D.C. believes that diffusion plays an important part in the problem; so much that he prefers to consider that the body saturates and desaturates as a single unit rather than as separate time units.

There is experimental evidence to support both theories and it is quite likely that both theories play an equally important part when using a gas as highly diffusible as helium.

Earlier investigators of the use of helium in diving made fundamental errors in their methods of calculation. These errors led to discouragement and prevented advancement of the problem. For instance, it was believed that if a mixture of half nitrogen and half helium were used that each of the two gases would act independently toward bubbling and that decompression needed would be only half because of breathing this mixture. This error led the British to report unfavorably on the possible use of helium and led our experimenters into serious trouble resulting in many cases of bends.

There can be no doubt that the peculiar mental effect that is experienced when exposed to high air pressure is caused by the nitrogen. This effect becomes so serious when divers reach depths beyond about 200 feet that many of them are unable to perform even the simplest tasks. Some even become unconscious at depths around 300 feet. A number of writers have claimed that the effect was caused by excess oxygen "burning up the tissues", "oxygen jag", or "oxygen poisoning". That this is not the case has, fortunately, been clearly demonstrated by Behnke in his work at Harvard - and by repeated exposures to high oxygen pressures by men of the Experimental Diving Unit, Navy Yard, Washington, D.C.

The groggy feeling or sense of depth is not experienced when men are breathing helium mixtures even to pressures corresponding to 500 feet, 16 atmospheres. Some forty divers have breathed the helium oxygen mixtures at various depths and the concensus of opinion seems to be that they sense a depth of about 1/4 of the actual depth to which they are exposed. Since helium is about 1/6 the weight of air it was natural to conclude that the groggy effect of air was caused by the weight of the gas in solution in the blood and possibly certain tissues. In order to develop this theory, a quantity of argon gas was obtained. Argon having a molecular weight of about 40 as compared to nitrogen 28 and helium 4, should cause the divers to feel deeper than when breathing air.

All divers who breathed argon-oxygen mixtures reported that they felt about 50% deeper than their actual depth, each was given a different depth and the information as to the actual depth was withheld from them. At a depth of three hundred feet breathing was very difficult, vision was impaired and a feeling of extreme giddiness was experienced.

An interesting experiment was carried out using the yeoman attached to the unit, L. B. Poush as a subject. Being an expert typist, it was felt that he could best demonstrate the efficiency of continued mental and physical coordination. He was placed in the recompression chamber with his typewriter suitably arranged so that he could breathe through a mask and at the same time copy a standard typing exercise. The pressure being raised to a point corresponding to 200 feet depth, first breathing air and next breathing a helium oxygen mixture, Poush copied from the exercise book for five minute periods. Upon completion of the tests he stated that he felt that he had done better when breathing air. Actually he had made nearly three times as many errors, even to the point of skipping whole lines, while breathing air. Yet, his sense of well being sometimes described as intoxication, caused him to believe that he had done well while he was quite conscious of having made some errors while breathing helium-oxygen.

It thus appeared very convincing that the weight of the carrier gas has a decided influence upon the mental condition of the diver.

From the standpoint of mental effect alone it seems that divers should be able to go to a depth of one thousand feet and perform useful work while breathing helium-oxygen mixtures.

The question naturally arises as to why use helium, or nitrogen or any other gas than oxygen. If it were possible to use pure oxygen, it would certainly provide an ideal solution, for no decompression would be necessary, since the tissues would use up the oxygen as fast as the blood could deliver it. A man at rest uses about 250 cc of oxygen per minute and performing very hard work about 4 liters per minute. The blood stream can carry in a rough figure about 800 cc of oxygen. There seems to be a limiting figure on the amount of oxygen that the body can stand in physical solution. Within the safe ranges of oxygen pressures, the amount of oxygen held in physical solution is reduced by the action of the blood haemoglobin combining chemically with this oxygen. This action creates the partial pressure vacancy which in turn causes the carbon dioxide to enter into solution to be carried off from the tissues. It seems to follow that if this partial pressure vacancy is destroyed by the fact that the oxygen in solution becomes greater than the amount that the haemoglobin has lost and can absorb, that the elimination of CO_2 will be delayed with subsequent harmful effects.

When symptoms are produced by breathing excess oxygen they are almost immediately and completely removed by lowering the partial pressure of the oxygen breathed.

The effects appear as ringing in the ears, sudden drowsiness, twitching of the muscles or emotional feelings such as irritability. The symptoms may develop rapidly into serious convulsions. For this reason there should be no delay in removing the cause.

It is a distinct advantage to use as high an oxygen percentage as is safe so as to keep the partial pressure of the helium at as low a level as possible. For instance if two and one half atmospheres is safe to breathe and it is desired to dive at 100 foot depth we would use a mixture of 62.5% oxygen and 37.5% helium. This is obtained as follows: 100 feet is 3 atmospheres gauge or 4 atmospheres absolute, which divided into 21/2 atmospheres, the limit of oxygen desired, gives 62.5%. The helium partial pressure would be 37.5% of (100 plus 33) or 50 feet. Since the body may be saturated to 1.7 x 33 or 56 feet partial pressure without requiring decompression, it follows that the time that a person can remain at 100 feet gauge, without decompression, is unlimited if two and a half atmospheres of oxygen is used. On the other hand if a percentage mixture equivalent to air were used the partial pressure would be 80% of 133 feet or 106 feet and the diver would have to stop for decompression at 106/1.7 equals 62.5 minus 33 or 29.5 feet gauge. The length of this and subsequent stops would depend upon the length of the exposure on the bottom.

Thus the partial pressure vacancy created by oxygen is used to its maximum advantage. The principle is also used for decompression and pure oxygen is used for stages at and below sixty feet.

As previously stated the gas comes out of the tissues into the blood stream during decompression. The rate of elimination depends upon the difference in partial pressure between that of the tissues and that of the blood. Consequently, if the partial pressure of the helium in the blood is reduced to zero by breathing oxygen the maximum flow of the helium into the blood stream will be effected and decompression will take place in a minimum of time.

Following a helium dive, decompression may be given with helium, air or oxygen. The method of computing this decompression is the same in general for all cases. If the maximum partial pressure of oxygen is desired, the percent oxygen is obtained as previously stated, that is 2.5 divided by the depth expressed in atmospheres absolute.

The consensus of opinion of all writers on this subject seems to be that no matter what respirable gas is being breathed the carbon dioxide in the alveolar air of the lungs will be about 5.3% and the water vapor about 6.2%. These percentages will vary inversely with the pressure.

The alveolar oxygen percentage will be less than that breathed by the amount of the carbon dioxide and also by a proportional amount of the water vapor percentage for the pressure.

Thus at one atmosphere 20% oxygen will be reduced first to 20 minus 5.3 or 14.7% for the carbon dioxide and then to 14.7 over 106.2 times 100 or 13.9% by reason of the water vapor. Thus we should expect to find about 14% oxygen in the arterial blood.

In the venous blood it has been determined that there is about 5.3% oxygen after the haemoglobin has partially restored itself by taking up the excess in solution.

The carbon dioxide being about 5.3% in the alveolar air will also be that amount in the arterial blood, but will increase to something over 6% in the venous blood.

To summarize the blood will contain the following gases:

	Arterial	Venous
Nitrogen	74.5	74.5
Water vapor	6.2	6.2
Carbon dioxide	5.3	6.0
Oxygen	14.0	5.3
TOTAL	100.0	92.0

The difference between these two totals, 8% represents the partial pressure vacancy.

Similarly at two atmospheres the amounts will be as follows:

	Arterial	Venous
Nitrogen	76.8	76.8
Water vapor	3.1	3.1
Oxygen	17.4	3.7
Carbon Dioxide	2.7	3.0
TOTAL	100.0	86.6

The partial pressure vacancy will be 13.4%.

While the oxygen percentage does increase a small amount of this is the percentage of one atmosphere and at pressures in excess of one atmosphere the figure must be divided by the pressure expressed in atmospheres to obtain the true percentage of the total.

The following table shows the partial pressure vacancy for each atmosphere up to ten:

Atmosphere	Partial Pressure Vacancy (percent)
1	8.0
2	13.4
3	15.3
4	16.2
5	16.9
6	17.5
7	18.0
8	18.3
9	18.6
10	18.9

These values are for a mixture of gas containing 20% oxygen and they will vary for different mixtures.

It is convenient for plotting the curve of saturation to take time units in ten minute increments up to 60 minute tissues. The time units of each tissue are obtained by dividing the time of the exposure by each time unit. While it is not accurate, it is customary to include the time going to the bottom in the exposure. Actually only half of this time should be included. With the time units obtained, the per cents of saturation are obtained from the table given in Figure 1. These percentages are multiplied by the partial pressure of the gauge depth to give the increased partial pressure of each tissue. Since the body is in a state of full saturation for one atmosphere, each of the partial pressure increases must be added to 27 which is the partial pressure of 1 atmosphere. The next step is the very important one of determining the first stop for decompression. It has been stated previously that when the body is fully saturated the ratio of the partial pressure to the absolute depth to which a diver may ascend is as 1.7 is to 1. While at shallow depths for short exposures it seems that the faster tissues can stand a greater ratio than 1.7 to 1, it appears to be quite safe and is not very wasteful in time to consider this 1.7 to 1 ratio for all tissues and all conditions, for it seems that helium is released in the tissues faster than the blood stream can carry it off and that a substantial stop at a position calculated in this manner is necessary. The partial pressure of the five minute tissue is divided by 1.7 for a trial first stop. This figure is absolute depth and 33 feet must be subtracted from it to obtain the gauge depth. The partial pressure corresponding to this depth is then calculated and using this figure and the partial pressure on the bottom the average partial pressure in going to the first stop is obtained.

The time of ascent to this stop is taken from the table of Rates of Ascent. This time is then divided by 5 to obtain the time units. From the table Figure 1 the percentage is taken. This is the percentage of the differential pressure that the five minute tissue will lose. The difference in pressure is obtained by subtracting the average partial pressure coming to the stop from the partial pressure of that tissue on the bottom. By subtracting the amount lost from the amount on the bottom we get the partial pressure upon arrival at that stop. Again dividing by 1.7 a new first stop is obtained. This process may be repeated until the minimum first stop is obtained. It is advisable to work out the ten minute tissue as well for it sometimes happens that it controls the first stop. For sake of convenience stops are always made at even ten foot marks, and when the first stop is finally selected it should be the 10 foot mark next deeper than the calculated figure, unless this happens to come to a figure exactly divisible by 10.

The time at all first stops should be 7 minutes for it has been found by experience that this amount of time is required to eliminate the initial outrush of released helium. This time comes in handy for the diver to get on his stage or to enter the submersible decompression chamber.

The next step is to calculate the loss or gain of all of the other tissues in coming to the first stop. This is accomplished in the same manner as above. The gain or loss in all tissues for the stay at the first stop is next calculated. The partial pressure corresponding to the first stop is the percentage of all other gases times the absolute depth. The elgebraic sum of the partial pressure of the stop gives the differences in pressure. The signs are minus or plus as the tissues are losing or gaining. The time level minutes is divided by each time tissue giving the corresponding time units. From Table I, the corresponding percentages are obtained. These percentages are multiplied by their corresponding differences in pressure which gives the loss or gain in partial pressure during this part of the decompression. The next stop is determined by dividing the maximum partial pressure of the gases by the ratio 1.7 and subtracting 33. The partial pressure of this stop is obtained and the differences in pressure are determined. From this point, a little different procedure is followed. The absolute pressure of the next stop is multiplied by 1.7 in order to obtain the maximum allowable partial pressure for the next stop. This figure is subtracted from the partial pressure of the tissues which are greater in order to find the amount to lose. The <u>amount</u> to lose divided by the corresponding difference in pressure gives the <u>percent to lose</u> for each tissue. From Table I, the corresponding time units are obtained. These time units are multiplied by their tissue times. The results give the times that it will take the various tissues to lose a sufficient amount to enable the diver to ascend to his next stop. The maximum time obtained from the various tissues is, of course, selected as the time of the stop. The amount that each tissue gains or loses is then calculated and applied.

This process is repeated until the diver is ready to surface. If oxygen is used after arrival at 60 feet the partial pressure of the stop is very much reduced and the stops may be figured the same as above except that it is not necessary to hurry the stops after 50 feet is reached because nearly maximum decompression will take place even though surfacing from the 50 foot stop. It has been found that when surfacing from 50 feet while breathing oxygen it is good safe practice to use the last five minutes of the time to come up to the surface at the rate of 10 feet per minute.

RATE OF ASCENT

In computing the rate of ascent to the first stop we have attempted to prevent a state of super-saturation in the venous blood. Since the blood in the veins has a partial pressure vacancy which nearly corresponds to the oxygen percentage being breathed, the pressure may be reduced by that amount without creating a state of super saturation. During the ascent to the first stop, after an exposure to excess pressure, it is extremely important to avoid the starting of bubble formation in the blood stream, for if it is once started, gas diffuses into the bubbles and the size of the bubbles increases. The danger, like a snowball rolling downhill, increases as the pressure is lowered and it is very doubtful that a blockage of blood vessels can be avoided. Consequently the rate of ascent should be regulated upon the basis of per cent change in pressure as well as the per cent of oxygen being breathed. If we can assume that the venous blood clears itself through the lungs in forty seconds, the rate of ascent can be calculated. This assumption is probably correct for since using this method of ascending to the first stop, no cases of bends have been encountered that could be traced to this part of the decompression.

Further evidence of the correctness of this theory was reported by Lieutenant W. A. New, U.S. Navy, Officer in Charge of the Diving School. When breathing air and ascending to the first stop at the usual fifty feet per minute many of the divers developed pronounced itch on the surface of their bodies. He reduced the rate of ascent to 25 feet per minute and no further symptoms were encountered. It is well known that this itch is a form of bends and that it indicates that a dangerous border line is being approached in the decompression procedure.

As an example of calculation of the correct rate of ascent we will take two cases, one 20% oxygen, the other 15%. Owing to the influence of water vapor an CO_2 in the lungs the oxygen tension in the lungs for the first atmosphere is 20% minus 6% CO_2 over 1.062 for water vapor, or about 13.2%. For the second atmosphere it will be 20 plus 13.2 divided by 2 or about 16.6% etc.

The following table shows these approximate amounts:

Atmospheres	Oxygen Per Cent (15)	Oxygen Per Cent (20)
1	8.5	13.2
2	11.8	16.6
3	12.8	17.7
4	13.4	18.3
5	13.7	18.6
6	13.9	18.8
7	14.1	19.0

Consider coming up from 200 feet to 167 feet a rise of 33 feet. The per cent change in pressure is from 7 to 6 atmospheres or 14.3%. When breathing 20% oxygen, the actual per cent at 7 atmospheres taken from the table above is 19. The time of ascent should be 14.3/19 or .75 times the time interval which it takes for the blood to clear (.67 minutes) or .5 minutes. The rate per minute will be 33 over .5 equals 66 feet per minute. The change in going from 100 to 67 feet would be 25%. The time (25 divided by 18.3) x .67 equals 91 and the rate 33/.91 about 36 feet per minute. Likewise the rate when coming from 66 feet to 33 feet would be about 26 feet per minute and from 33 to the surface 17 feet per minute.

In view of the large number of cases where men have greatly exceeded these rates of ascent without apparent symptoms it would seem that they are greatly exaggerated. However, when the time involved is such time as would be otherwise used for decompression, it is felt that it would be an added comfort to be able to feel that the probability of starting bubbles in this manner is eliminated.

If 15% oxygen is breathed the rate of as-ent from 200 to 167 feet would be 49 feet per minute.

The rates would compare as follows:

Ascent	20% Oxygen	15% Oxygen
200 to 167	66 ft. per min.	49 ft. per min.
167 to 133	56 ft. per min.	41 ft. per min.
133 to 100	46 ft. per min.	34 ft. per min.
100 to 67	36 ft. per min.	27 ft. per min.
67 to 33	26 ft. per min.	19 ft. per min.
33 to 0	17 ft. per min.	12 ft. per min.

It is recognized that there is a small amount of oxygen carried in the venous blood (5 to 13.5% of an atmosphere) and that this reduces the partial pressure vacancy. This has not been used in the above discussion but has been incorporated in the table of rates of ascent.

This has been applied by computing the oxygen percent or an atmosphere in the venous blood for each atmosphere of pressure. The oxygen varies from 5.3% when breathing 20% at one atmosphere or 1/5 of an atmosphere effective to 13.5% when breathing three atmospheres effective oxygen. The per cent of an atmosphere is then divided by the number of atmospheres of pressure to get the actual per cent for that pressure. This per cent is subtracted from the per cent of alveolar oxygen to obtain the true partial pressure vacancy in the venous blood.

It is evident from the following table of Rates of Ascent that as the oxygen percentages are reduced for the purpose of preventing high tensions of oxygen on deep dives, care must be taken to not exceed the proper rate of ascent.

TABLE OF RATES OF ASCENT FEET PER MINUTE

Depth at Point ascent begins	OXYGEN PER CENT - DRY SAMPLE												
	10	15	20	25	30	35	40	45	50	55	60	54	70
600	56	132											
550	51	118	157										
500	46	106	143										
450	42	97	132										
400	37	87	118	150									
350	32	76	103	135	159								
300	27	65	89	114	137	161							
250	22	52	72	94	115	137	159						
200	16	41	58	75	92	109	126	143	160				
150	12	30	43	57	71	85	99	113	127	141	155		
100	7	21	30	40	50	60	70	80	90	100	110	120	130
50	3	10	17	23	29	35	41	47	53	60	67	74	80

Since it is not practical to use such odd figures when bringing a diver up to his first stop this table will be rearranged. It is never practical to bring a diver up at a greater rate than 75 feet per minute.

TABLE OF RATES OF ASCENT FEET PER MINUTE

Depth at Point ascent begins	OXYGEN PER CENT - DRY SAMPLE										
	10	15	20	25	30	35	40	45	50	55	60
600	50										
550	50										
500	40		ALL	OTHERS ÷ 75			FEET	PER MINUTE			
450	40										
400	30										
350	30										
300	20	50									
250	20	50									
200	10	40	50								
150	10	30	40	50							
100	10	20	30	40	50						
50	10	10	20	20	30	30	40	50			

(B)

EXAMPLE OF COMPUTATION OF A DECOMPRESSION TABLE FOR USE WITH HELIUM-OXYGEN DIVING

This example differs from the actual computations as follows:

(a) The minimum tissue sued is 60 minute where as in the tables submitted the 70 minute tissue was used.

(b) The time of exposure was a "rest" time while the tables submitted are for "work" time, which is twice "rest" time.

(c) All tables are calculated considering the mixture used during decompression to be 16% oxygen in order to be on the safe side. In the example, 25% is used.

An example of computing a decompression table follows and the curves of this decompression are shown in Figure 2.

Suppose the depth selected is 300 feet, the time on the bottom 30 minutes, and that the gas breathed is helium and 25% oxygen.

Example of computation of Decompression Table:

Depth - 300 feet.
Time on bottom - 30 minutes.
Gas used - 25% oxygen - 75% helium.
Effective oxygen 25 minus 2 equals 23% (Allowing for a small amount of oxygen in venous blood and loss in helmet).
Absolute depth of dive is 300 plus 33 equals 333 feet
PP of all other gases 77 (100 - 23% 02) times 333 equals 256.4.
PP increase saturation effect 77 times 300 equals 231.
All calculations are made to the nearest foot

Tissue saturation is obtained as follows:

1 Tissue	2 Time Units	3 %Saturation	4 PP increase	5 Total
5	6	98.5	228	255
10	3	87.5	202	229
20	1.5	64.6	149	176
30	1	50	116	143
40	.75	40.5	94	121
50	.6	34	79	106
60	.5	29.3	68	95

1 - Tissues selected to plot curve.
2 - Time of exposure divided by tissue time.
3 - From Table I.
4 - Percentage (column 3) times 231.
5 - 27 feet plus increase (column 4).

Trial first stop 255 divided by 1.7 equals 150 feet, 117 feet gauge.

Using next higher 10 foot mark, the stop is 120 feet.

From the table of Rates of Ascent when using 23% oxygen, we may come from 300 feet to 250 feet at 104 feet per minute,
250 feet to 200 feet at 75 feet per minute,
200 feet to 150 feet at 63 feet per minute,
150 feet to 120 feet at 50 feet per minute.

For practical purposes the diver should not be brought up at a rate greater that 75 feet per minute. The time of ascent to 120 feet would be 3 minutes. Using the average partial pressure in coming to the first stop is accurate enough for determining the change of partial pressure in the various tissues and the figure is determined by adding the bottom pressure to the pressure of the stop and dividing by two: 256 plus (153 times 77) over 2 equals 187 feet.

Check first stop.

1 Tissue	2 PP	3 Av.PP	4 DP	5 Time	6 TU	7 %	8 Loss	9 PP at	10 1st Stop
5	255	187	68	3M	.6	34	23	232	136
10	229	187	42	3M	.3	18.7	8	221	

Stop will be 136 - 33 equals 103 feet and 110 will be used.

1 - Tissues to be considered.
2 - From saturation and calculation.
3 - Calculated above.
4 - Column 2 less column 3.
5 - Time of ascent.
6 - Column 5 divided by column 1.
7 - Taken from Table 1.
8 - Column 4 times column 7.
9 - Column 2 less column 8.
10 - Maximum amount in column 9 divided by 1.7.

The average pp when coming to 110 feet gauge or 143 feet absolute will be 256 plus (143 times 77) over 2 or 183 feet.

There will be no change in the time of ascent.

The change in pp of all tissues when coming to 110 feet gauge is computed as follows:

1 Tissue	2 PP	3 Av.PP	4 DP	5 TU	6 %	7 Gain or Loss	8 PP
5	255	183	-72	.6	34	-24	231
10	229	183	-46	.3	18.7	- 9	220
20	176	183	+ 7	.15	9.8	+ 1	177
30	143	183	+40	.1	6.6	+ 2	145
40	121	183	+62	.075	5.0	+ 3	124
50	106	183	+77	.06	4.0	+ 3	109
60	95	183	+88	.05	3.4	+ 3	98

1 - Tissues.
2 - pp saturation.
3 - Computed above.
4 - Column 3 minus column 2.
5 - Time units for 3 minutes; 3 divided by column 1.
6 - Percentages for TU in column 5, Table 1.
7 - Column 4 times column 6.
8 - Column 2 plus or minus column 7.

Change in partial pressure as a result of remaining at first stop for 7 minutes

1 Tissue	2 PP	3 PPofStop	4 DP	5 TU	6 %	7 Change	8 PP
5	231	110	-121	1.4	62.1	-75	156
10	220	110	-110	.7	38.4	-42	178
20	177	110	-67	.35	21.5	-14	163
30	145	110	-35	.233	14.9	-5	140
40	124	110	-14	.175	11.4	-2	122
50	109	110	+1	.14	9.2	0	109
60	98	110	+12	.12	8	+1	99

1 - Tissues.
2 - pp at arrival at 110 feet.
3 - (110 plus 33) times 77 equals 110.
4 - Column 2 less column 3.
5 - 7 minutes divided by column 1.
6 - Table 1.
7 - Column 4 times column 6.
8 - Column 2 plus or minus column 7.

It will be noted that the highest point on the curve of saturation will be near the 10 minute tissue and the 10 minute tissue will be used for computing the next stop. 178 divided by 1.7 equals 105 minus 33 equals 72.

One minute should be allowed for bringing the diver to the next stop and the 10 minute tissue will lose about 5 feet in this time so the next stop will be 70 feet.

The average pp will be 110 plus (103 times 77 over 2 or 95.

The change during the ascent will be as follows:

Tissue	PP	Av.PP	DP	TU	%	Change	PP
5	156	95	-61	.2	12.9	-8	148
10	178	95	-83	.1	6.6	-5	172
20	163	95	-68	.05	3.4	2	161
30	140	95	-45	.033	2.2	-1	139
40	122	95	-27	.025	1.7	0	122
50	109	95	-14	.02	1.3	0	109
60	99	95	-4	.017	.9	0	99

At 70 feet it will be necessary to remain until the maximum tissue reaches the absolute pressure of the next stop 60 feet times 1.7 or (60 plus 33) times 1.7 or 158.

The highest tissue, 10 minute, has 172 feet and must lose 172 minus 158 or 14 feet. The difference in pressure will be 178 minus pp of stop (103 times 77) or 99. 14 feet is 14/99 or 14.1% and from Table I this is .22 time units. The time that it will take the 10 minute tissue to lose 14 feet will be 10 times .22 or 2.2 minutes. Since it is more convenient to use even minute intervals the stop will be taken as 3 minutes.

The change will be as follows:

Tissue	PP	Av.PP	DP	TU	%	Change	PP
5	148	79	69	.6	34	-23	125
10	172	79	93	.3	18.7	-17	155
20	161	79	82	.15	9.8	-8	153
30	139	79	60	.1	6.6	-4	135
40	122	79	43	.075	5.0	-2	120
50	109	79	30	.06	4.0	-1	108
60	99	79	20	.05	3.4	-1	98

The decompression from this point may be effected by using pure oxygen or by continuing with the same mixture. Both methods will be computed for comparison. The time for ascending ten feet is not computed separately but is part of the time of the next stop. While the 10 minute tissue is actually highest, it will hose more than the 20 minute tissue and the 20 minute tissue will control.

The 20 minute tissue has 153 feet and has to be reduced to (50 plus 33) times 1.7 equals 141, before coming to 50 feet. It must, therefore, lose 12 feet.

The difference in pressure will be 153 minus 72 (93 times 77) equals 81. The per cent to lose will be 12/81 equals 14.8 and from Table I the TU will be .23. Time will be 20 times .23 or 4.6 minutes. The time will be taken as 5 minutes.

Change while at 60 feet will be as follows:

Tissue	PP	Av.PP	DP	TU	%	Change	PP
5	125	72	53	1	50	-27	98
10	155	72	83	.5	29.3	-24	131
20	153	72	81	.25	15.8	-13	140
30	135	72	63	.167	10.8	- 7	128
40	120	72	48	125	8.3	- 4	116
50	108	72	36	1	6.6	- 2	106
60	98	72	26	.083	5.5	- 1	97

It is not necessary to continue the 5 and 10 minute tissues.

At 50 feet the 20 minute tissue must be reduced to 124 in order to proceed to the 42 foot level and must lose 16 feet. This is 16/76 or 21% which is .34 TU. Time is .34 times 20 equals 6.8 minutes. Time will be 7 minutes.

Change while at 50 feet:

Tissue	PP	Av.PP	DP	TU	%	Change	PP
20	140	64	76	.35	21.5	-16	124
30	1 8	64	64	.233	14.9	-10	118
40	116	64	52	.175	11.4	- 6	110
50	106	64	42	.14	9.2	4	102
60	9	64	33	.12	8	-3	94

The 30 minute tissue will now control and at 40 feet it will have to be reduced to 63 times 1.7 equals 107 before it will be safe to come to 30 feet. It must lose 11 feet or 11/62 equal 1 .8%. This is 28 TU times 30 equals 8.4 min. and the stop will be 9 min.

Tissue	PP	Av.PP	DP	TU	%	Change	PP
30	118	56	62	.3	18.7	-12	106
40	110	56	54	.225	14.4	-8	102
50	102	56	46	.18	11.7	-5	97
60	94	56	38	.15	9.8	-4	90

The 40 minute tissue will now control and at 30 feet it will have to be reduced to 53 times 1.7 equals 90 before it will be safe to come to 20 feet. It must lose 12 feet or 12/53 or 22.6% equals 37 TU times 40 equals 14.8. The stop will be 15 minutes.

Tissue	PP	Av.PP	DP	TU	%	Change	PP
40	102	49	53	375	22.8	-12	90
50	97	49	48	.3	18.7	-9	88
60	90	49	41	.25	15.8	-6	84

The 50 minute tissue now controls and at 10 feet it will have to be reduced to 43 times 1.7 equals 73 before it will be safe to come to 10 feet. It must lose 15 feet or 15/47 equals 31.9% or .55 TU. The time will be 50 times .55 or 27.5 minute. The stop will be 28 minutes.

Tissue	PP	Av.PP	DP	TU	%	Change	PP
50	88	41	47	.56	32.2	-15	73
60	84	41	43	.47	27.8	-12	72

The 60 minute tissue now controls and at 10 feet it will have to be reduced to 33 times 1.7 or 56 feet before surfacing. It must lose 16 feet. The difference in pressure is 72 minus 33 equals 39. Per cent to lose equals 16/39 or 41%. TU equals .763. Time will be 60 times .763 equals 45.78 or 46. minutes.

Since it is safe to use oxygen at 60 feet for short periods a great saving of time will be accomplished by shifting to oxygen at that point.

When shifting to oxygen at 60 feet the suit is ventilated by admitting 18 cubic feet of oxygen into the helmet over a period of one minute. This gives about 80% oxygen mixture for breathing and the best conditions from the standpoint of gas expended and time saved, are obtained.

When using the submersible decompression chamber, pure oxygen can be breathed through a mask and the best decompression effected thereby. The following computations will be based upon 80% oxygen.

At 60 feet the pp on all other gases will be 93 times 20 or 19. The diver will be kept at 60 feet for 10 minutes. This is more than ample, but very little advantage is gained by dropping pressure. In fact better decompression is obtained at 50 feet than at 10 feet when breathing pure oxygen.

The change while at 60 feet for 10 minutes will be as follows: *

Tissue	PP	PPStop	DP	TU	%	Change	PP
5	98	19	79	2	75	-59	39
10	131	19	112	1	50	-56	75
20	140	19	121	.5	29.3	-35	105
30	128	19	109	.33	20.6	-22	106
40	116	19	97	.25	15.8	-15	101
50	106	19	87	.2	12.9	-11	95
60	97	19	78	.167	10.8	- 8	89

At 50 feet the pp will be 20% times 83 equals 17.
The 30 minute tissue controls.
The times to reduce all tissues to 56 will now be computed:

Tissue	PP	PPStop	DP	PP to lose	% to lose	TU	Time
30	106	17	89	50	56.2	1.19	35.7
40	101	17	84	45	53.5	1.11	44.4
50	95	17	78	39	50	1.0	50
60	89	17	72	33	45.8	.885	53.1

PP to lose is found by subtracting 56 from the pp of the tissues. Percent to lose is found by dividing pp to lose by DP. Time is found by multiplying tissue by TU. The maximum time will be 53.1 or 54 minutes will be used.

*Note: It is more accurate to consider the first 3 minutes at this stop as breathing the Hilium Oxygen mixture - in order to allow for rinsing out the lungs with oxygen.

The two tables are shown for comparison.

		On helium-oxygen mixtures	Going on oxygen at 60 feet.
To stop	110	3 minutes	3 minutes
at	110	7 minutes	7 minutes
to	70	1 minute	1 minute
at	79	3 minutes	3 minutes
at	60	5 minutes	10 minutes
at	50	7 minutes	54 minutes
at	40	9 minutes	
at	30	15 minutes	
at	20	28 minutes	
at	10	46 minutes	
	TOTALS ---	124 minutes	78 minutes

It must be recognized that in computing the foregoing tables, that if a lower percentage of oxygen were used and the same pp of AOG were used for the dive, the loss at each stop would be less because the pp of AOG is increased with the reduction in oxygen pp. This would result in a smaller difference in pressure and consequently less loss in pp at each stop.

The same exposure 256 feet pp, but with 10% oxygen has been computed to show this difference. The gauge depth would be only 250 feet, and the rate of ascent to the first stop would be less.

Using 25% oxygen 300 feet gauge, 256 feet pp A.O.G.			Using 10% oxygen 250 feet gauge, 256 feet pp A.O.G.	
to 110 feet	3 min.	to	110 feet	6 min.
at 110 feet	7 min.		110 feet	7 min.
to 70 feet	1 min.		70 feet	1 min.
at 70 feet	3 min.		70 feet	3 min.
at 60 feet (Breathing)	10 min.		60 feet	10 min.
at 50 feet (Oxygen)	54 min.		50 feet	60 min.

Another point to be considered is that the partial pressure of (all other gases) AOG in the first atmosphere has a tendency to equalize toward the pp which would result from the percentage of oxygen breathed during the exposure.

If when calculating the table, it is considered that the pp of AOG in the first atmosphere is never reduced any errors introduced will be in the direction of safety.

Since it is not always convenient to mix the helium and oxygen in the exact proportions desired, decompression tables have been arranged in two parts. First, a table of partial pressures and depths for different oxygen percentages has been arranged. Having the depth of water and the oxygen percentage the partial pressure is picked out from the table. It is proper to interpolate to the nearest foot.

The probability of oxygen loss in the helmet due to respiration and the oxygen percentage in the venous blood which must be included in AOG have been included in determining the partial pressures of AOG in this table.

The second table shows decompression requirements for various partial pressures of AOG, and for various times of exposure, measured from the time that the diver starts down. In selecting the table interpolation is not allowed. If the time of exposure is not exactly given in the table the next higher time must be used. Likewise if the exact partial pressure is not found in the table the next higher partial pressure is used. These tables are computed upon the assumption that the diver is active while on the bottom.

FIGURE 1

PERCENTAGE FACTOR OF DESATURATION AS A FUNCTION OF THE TIME UNIT

Time Unit	0	1	2	3	4	5	6	7	8	9
0.0	---	0.5	1.3	2.0	2.7	3.4	4.0	4.7	5.3	6.0
0.1	6.6	7.3	8.0	8.6	9.2	9.8	10.4	11.0	11.7	12.3
0.2	12.9	13.5	14.1	14.7	15.3	15.8	16.4	17.0	17.6	18.2
0.3	18.7	19.3	19.8	20.4	21.0	21.5	22.0	22.5	23.1	23.7
0.4	24.2	24.7	25.3	25.7	26.3	26.8	27.3	27.8	28.3	28.8
0.5	29.3	29.7	30.2	30.7	31.2	31.7	32.2	32.6	33.0	33.5
0.6	34.0	34.4	34.9	35.3	35.8	36.2	36.7	37.1	37.5	38.0
0.7	38.4	38.8	39.3	39.7	40.1	40.5	40.9	41.3	41.7	42.2
0.8	42.5	42.9	43.3	43.7	44.1	44.5	44.9	45.3	45.6	46.0
0.9	46.3	46.7	47.1	47.5	47.8	48.2	48.5	48.9	49.3	49.6
1.0	50.0	50.3	50.6	51.0	51.3	51.6	52.0	52.3	52.6	52.9
1.1	53.3	53.6	53.9	54.3	54.5	54.8	55.2	55.5	55.8	56.1
1.2	56.4	56.7	57.0	57.3	57.6	57.9	58.2	58.5	58.8	59.1
1.3	59.3	59.6	59.8	60.2	60.5	60.7	61.0	61.3	61.5	61.8
1.4	62.1	62.3	62.6	62.8	63.1	63.3	63.6	63.8	64.1	64.3
1.5	64.6	64.8	65.0	65.3	65.5	65.7	66.0	66.3	66.5	66.7
1.6	66.9	67.2	67.4	67.6	67.9	68.1	68.3	68.5	68.7	68.9
1.7	69.2	69.4	69.6	69.8	70.0	70.2	70.4	70.6	70.8	71.0
1.8	71.2	71.4	71.6	71.8	72.0	72.2	72.4	72.6	72.8	72.9
1.9	73.2	73.3	73.6	73.7	73.9	74.1	74.3	74.5	74.6	74.8
2.0	75.0	75.2	75.3	75.5	75.6	75.8	76.0	76.2	76.4	76.5
2.1	76.6	76.8	76.9	77.1	77.3	77.4	77.6	77.8	77.9	78.0
2.2	78.2	78.4	78.5	78.6	78.8	79.0	79.2	79.4	79.5	79.6
2.3	79.7	79.9	80.0	80.1	80.3	80.4	80.5	80.6	80.8	80.9
2.4	81.1	81.3	81.4	81.5	81.6	81.7	81.8	82.0	82.1	82.3
2.5	82.4	82.5	82.6	82.7	82.8	83.0	83.1	83.2	83.3	83.4
2.6	83.5	83.6	83.7	83.9	84.0	84.1	84.3	84.4	84.5	84.6
2.7	84.7	84.8	84.9	85.0	85.1	85.2	85.3	85.4	85.5	85.6
2.8	85.7	85.8	85.9	86.0	86.1	86.2	86.3	86.4	86.5	86.6
2.9	86.6	86.7	86.8	86.9	87.0	87.1	87.2	87.3	87.4	87.5

Time Unit	0	1	2	3	4	5	6	7	8	9
3.0	87.5	87.6	87.7	87.8	87.9	88.0	88.0	88.1	88.2	88.3
3.1	88.4	88.5	88.5	88.6	88.7	88.8	88.9	89.0	89.0	89.1
3.2	89.2	89.3	89.4	89.4	89.5	89.5	89.6	89.7	89.8	89.8
3.3	89.9	90.0	90.0	90.1	90.2	90.2	90.3	90.4	90.5	90.6
3.4	90.6	90.6	90.7	90.8	90.8	90.9	90.9	91.0	91.0	91.1
3.5	91.2	91.2	91.3	91.4	91.4	91.5	91.5	91.6	91.6	91.7
3.6	91.8	91.8	91.9	91.9	91.9	92.0	92.0	92.0	92.1	92.2
3.7	92.2	92.3	92.4	92.4	92.5	92.5	92.5	92.5	92.6	92.6
3.8	92.7	92.8	92.8	92.9	92.9	93.0	93.0	93.0	93.1	93.1
3.9	93.2	93.2	93.3	93.4	93.4	93.5	93.5	93.5	93.6	93.6
4.0	93.7	93.7	93.8	93.8	93.9	93.9	94.0	94.0	94.0	94.1
4.1	94.1	94.1	94.2	94.2	94.2	94.3	94.4	94.4	94.4	94.5
4.2	94.5	94.5	94.5	94.6	94.7	94.7	94.8	94.8	94.8	94.9
4.3	94.9	95.0	95.0	95.0	95.0	95.1	95.1	95.1	95.2	95.2
4.4	95.3	95.3	95.4	95.4	95.4	95.5	95.5	95.5	95.5	95.5
4.5	95.6	95.6	95.6	95.7	95.7	95.7	95.8	95.8	95.8	95.9
4.6	95.9	95.9	95.9	96.0	96.0	96.0	96.0	96.0	96.0	96.0
4.7	96.0	96.1	96.1	96.1	96.2	96.2	96.2	96.2	96.3	96.3
4.8	96.3	96.3	96.3	96.4	96.4	96.4	96.4	96.5	96.5	96.5
4.9	96.5	96.5	96.5	96.5	96.6	96.6	96.6	96.6	96.6	96.7
5.0	96.7	96.7	96.8	96.8	96.8	96.8	96.9	96.9	96.9	96.9
5.1	97.0	97.0	97.0	97.0	97.0	97.1	97.1	97.1	97.2	97.2
5.2	97.2	97.2	97.2	97.2	97.3	97.3	97.3	97.4	97.4	97.4
5.3	97.4	97.5	97.5	97.5	97.5	97.6	97.6	97.6	97.6	97.6
5.4	97.7	97.7	97.7	97.7	97.7	97.8	97.8	97.8	97.8	97.8
5.5	97.8	97.8	97.9	97.9	97.9	97.9	97.9	97.9	98.0	98.0
5.6	98.0	98.0	98.0	98.0	98.0	98.0	98.1	98.1	98.1	98.1
5.7	98.1	98.1	98.1	98.1	98.2	98.2	98.2	98.2	98.2	98.2
5.8	98.2	98.3	98.2	98.3	98.3	98.3	98.3	98.3	98.4	98.4
5.9	98.4	98.4	98.4	98.4	98.4	98.4	98.5	98.5	98.5	98.5
6.0	98.5	98.5	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6

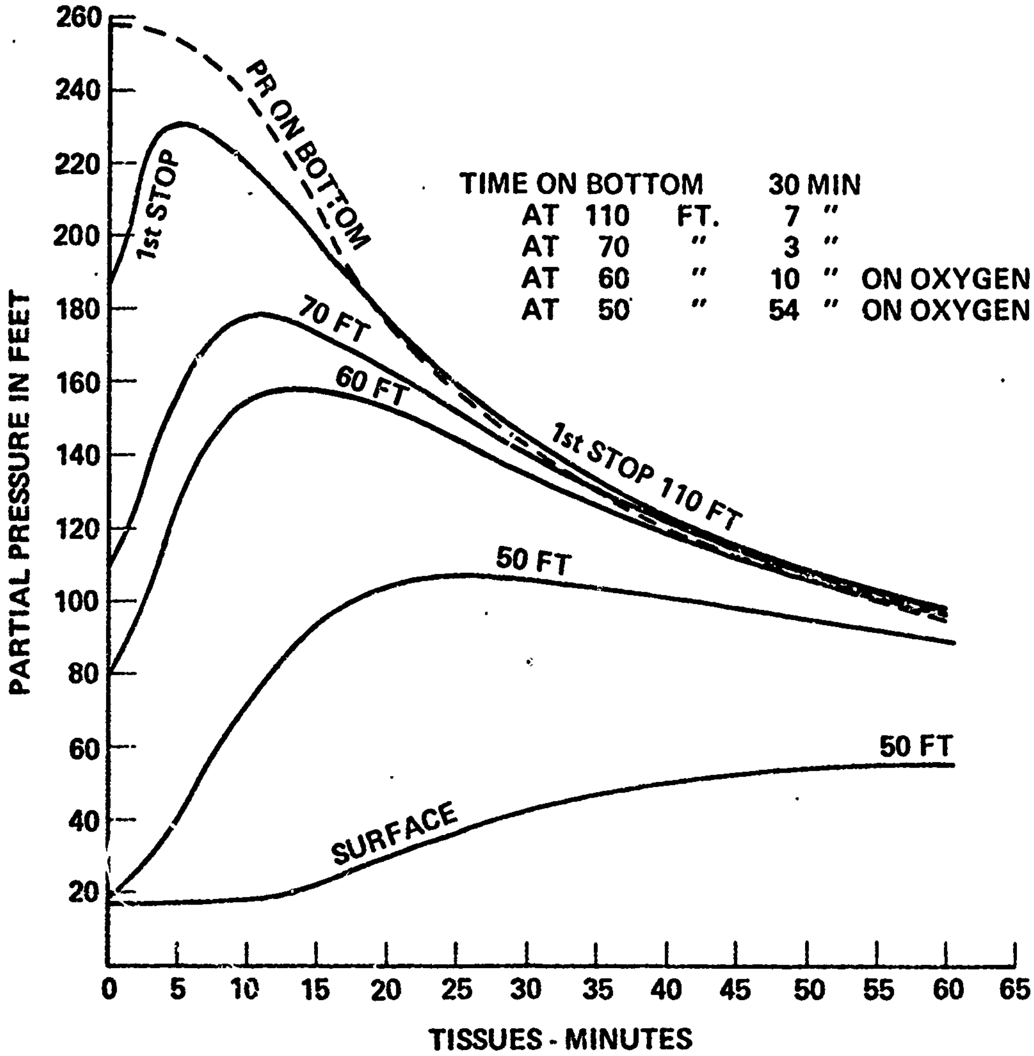


FIGURE 2.

CURVES ILLUSTRATE THE PROGRESS OF DESATURATION OF BODY AFTER SATURATION AT A PARTIAL PRESSURE OF 256 FEET FOR 30 MINUTES.

HELIUM
(C) DECOMPESSION TABLES UP TO 450 FEET

The following Decompression Tables are computed for all time and oxygen combinations and all depths up to 450 feet gauge.

While it may not be practical to dive for the longer periods, an emergency may arise where it will be necessary to have the tables.

All tables are computed with maxiumu safety factors and it is believed they are safe for all conditions to which a diver may be exposed.

Decompression on oxygen after arrival at 60 feet has been considered as standard.

Decompressions on Helium-Oxygen mixtures after arrival at 60 feet or on air from any depth will be considered emergencies and the tables provided herein are emergency tables, and are therefore for maximum exposures.

It is important to keep CO_2 below 2% effective.

These tables were computed by Lt. Comdr. C. B. Momsen, U. S. Navy, and Lieutenant (jg) K. R. Wheland, U. S. Navy, and it is requested that any apparent errors discovered be referred to either of them.

DECOMPRESSION TABLES

FOR USE WHEN DIVING IN SEA WATER WITH HELIUM-OXYGEN MIXTURES

Table for Depths up to 100 feet when decompression is not necessary for any exposure.

DEPTH IN FEET	OXYGEN PERCENTAGE
30	13 to 100
40	26 to 100
50	34 to 100
60	42 to 90
70	48 to 80
80	52 to 73
90	57 to 67
100	60 to 62
No Decompression Necessary	

HELIUM-OXYGEN

TABLE OF PARTIAL PRESSURES 10 FEET to 600 FEET

ENTER THIS TABLE - - - SELECT PARTIAL PRESSURES

	PERCENTAGE OF OXYGEN USED													
DEPTH	13	15	17	19	21	23	25	30	35	40	45	50	55	
10														*ND to 100%O2
20														*ND to 100%O2
30														*ND to 100%O2
40	65	64	62	61	59	58	56							*ND to 100%O2
50	74	72	71	69	68	66	64	60	56					*ND to 100%O2
60	83	81	79	78	76	74	72	67	63	58	53			*ND to 90% O2
70	92	90	88	86	84	82	80	75	69	64	59	54		*ND to 80% O2
80	101	99	96	94	92	90	87	82	76	71	65	59	53	*ND to 73% O2
90	110	107	105	103	100	98	95	89	83	77	71	65	58	*ND to 67% O2
100	119	116	113	111	108	105	103	96	90	83	76	70	63	
110	128	124	121	119	116	113	110	103	97	89	82	75	67	
120	136	133	130	127	124	121	118	110	103	95	87	80	72	
130	145	142	139	135	132	129	126	118	109	101	93	85		
140	154	151	147	144	140	137	133	125	116	107	99			
150	165	159	156	152	148	145	141	132	123	114	104			
160	172	168	164	160	157	153	149	139	129	120				
170	181	177	173	169	165	160	156	146	136	126				
180	190	186	181	177	173	169	164	154	143					
190	199	194	190	185	181	176	172	161	150					
200	208	205	198	194	189	184	180	168	156					
210	216	212	207	202	197	192	187	175						
220	225	220	215	210	205	200	195	183						
230	234	229	224	219	213	208	203	190						
240	243	238	232	227	222	216	211	197						
250	252	247	241	235	230	224	218							
260	261	255	249	243	237	231	225							
270	270	264	258	252	246	240	233							
280	280	273	267	260	253	247	241							
290	288	281	275	268	262	255	249							
300	297	290	283	277	270	263	257							

*(ND) - No decompression

TABLE OF PARTIAL PRESSURES - 10 FEET to 600 FEET (Continued)

	PERCENTAGE OF OXYGEN USED					
DEPTH	13	15	17	19	21	23
310	306	299	292	285	278	271
320	314	307	300	293	286	279
330	323	316	309	302	294	287
340	332	325	317	310	303	295
350	341	334	326	318	311	303
360	350	343	335	327	319	
370	359	351	343	335	327	
380	368	359	351	343	334	
390	377	368	360	351		
400	386	377	368	359		
410	395	386	377	368		
420	403	394	385	376		
430	412	403	394	385		
440	421	412	403			
450	430	420	410			
460	439	429	419			
470	448	438	428			
480	457	447	437			
490	466	456	446			
500	475	465				
510	484	473				
520	493	482				
530	502	492				
540	511	500				
550	520	509				
560	529	518				
570	538	527				
580	548					
590	557					
600	566					

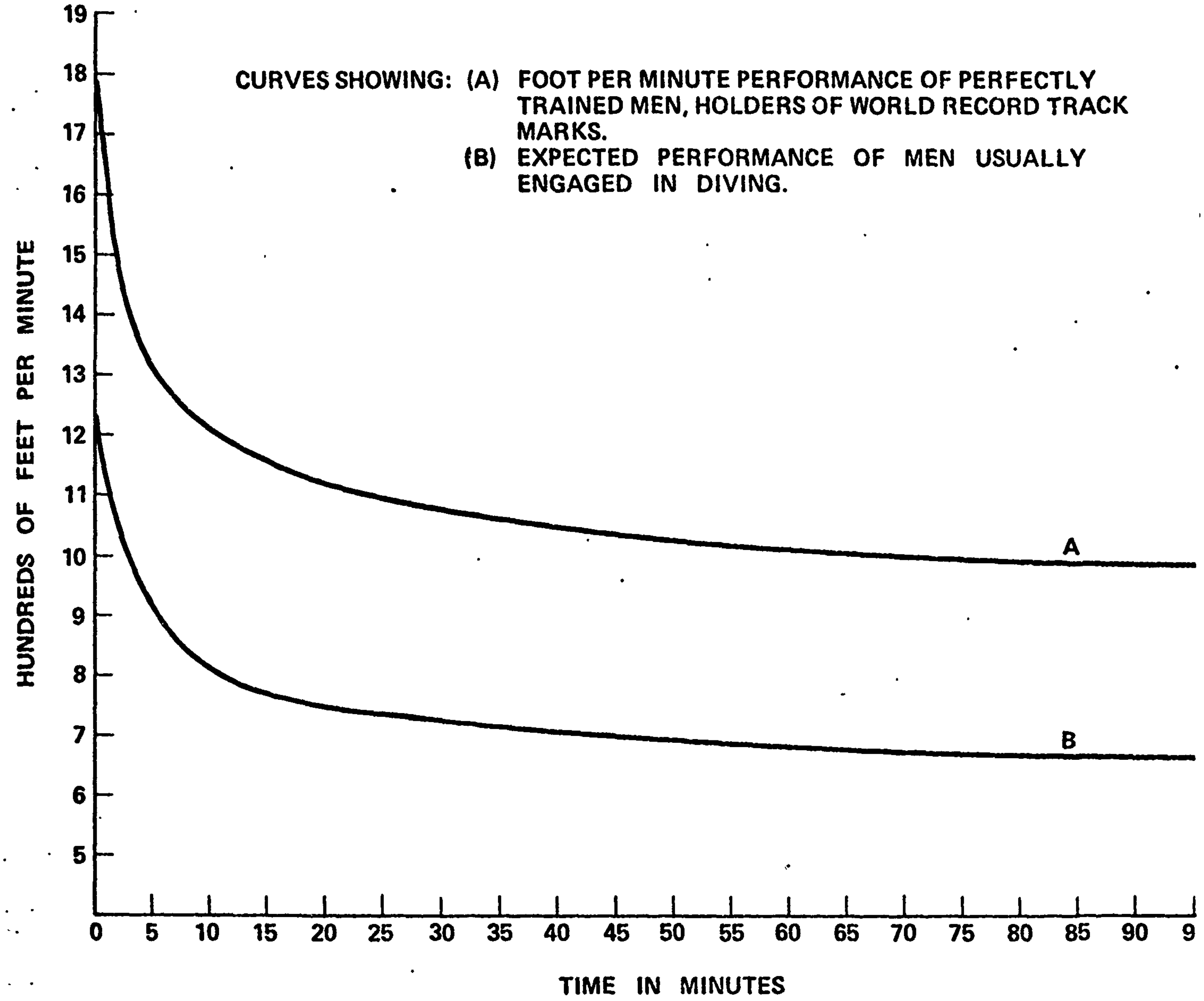


FIGURE 5.
TIME WORK CURVES

INSTRUCTIONS FOR USE OF OXYGEN DECOMPRESSION CURVES

Using depth of water and oxygen per cent to be breathed on the bottom, select parial pressure from "Table of Partial Pressures". Partial Pressure as used in these tables and the curve is obtained by the following formula:

100 - (02% - 2 x (D plus 33) D - is depth. 02% is per cent of oxygen in gas mixture used.

2. Use up to <u>141</u> feet partial pressure <u>ONLY</u>.

3. The limits of oxygen to be used are indicated in "Table of Partial Pressures".

4. All stops are at 50 feet gauge.

5. Breathe oxygen at 50 feet and until reaching surface.

Ventilate 25 cu.ft. and circulate remaining period.

6. Rate of ascent:

Up to 100 feet partial pressure ----------	1 minute.
Over 100 feet partial pressure ----------	2 minutes.
From 50 feet to surface ----------------	Last 5 mins. of dive.

OXYGEN DECOMPRESSION TABLES FOLLOWING HELIUM-OXYGEN DIVE

1. Using depth of water and oxygen per cent to be breath on the bottom, select partial pressure from "Table of Partial Pressures".

2. Using next higher partial pressure given in these tables and next higher "time of dive" including time of descent, select table of decompression.

3. The time of ascent unless indicated, will be included in the subsequent stop.

4. At 60 feet, ventilate 25 cu.ft. of oxygen and then circulate oxygen for the remaining period at 60 feet, and the entire time at 50 feet. If the first stop is at 50 feet, ventilate 25 cu.ft. of oxygen and then circulate oxygen for the remaining period. If using the submersible decompression chamber, oxygen is breathed through a mask at 60 feet and at 50 feet.

PARTIAL PRESSURE 60

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	0	2
20	2	0	2
30	2	0	2
40	2	0	2
60	1	4	5
80	1	7	8
100	1	10	11
120	1	12	13

PARTIAL PRESSURE 70

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	0	2
20	1	5	6
30	1	8	9
40	1	10	11
60	1	15	16
80	1	21	22
100	1	26	27
120	1	29	30
140	1	31	32
160	1	32	33

PARTIAL PRESSURE 80

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	1	4	5
20	1	9	10
30	1	14	15
40	1	18	19
60	1	26	27
80	1	34	35
100	1	42	43
120	1	46	47
140	1	48	49
160	1	49	50

PARTIAL PRESSURE 90

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	5	7
20	2	13	15
30	2	19	21
40	2	25	27
60	2	36	38
80	2	46	48
100	2	55	57
120	2	59	61
140	2	61	63
160	2	62	64
180	2	63	65

PARTIAL PRESSURE 100

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	6	8
20	2	17	19
30	2	26	28
40	2	33	35
60	2	46	48
80	2	57	59
100	2	65	67
120	2	70	72
140	2	73	75
160	2	74	76
180	2	75	77
200	2	76	78

PARTIAL PRESSURE 110

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	6	8
20	2	21	23
30	2	32	34
40	2	41	43
60	2	57	59
80	2	69	71
100	2	76	78
120	2	81	83
140	2	84	86
160	2	85	87
180	2	86	88
200	2	87	89

PARTIAL PRESSURE 120

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	8	10
20	2	27	29
30	2	38	40
40	2	48	50
60	2	65	67
80	2	78	80
100	2	86	88
120	2	91	93
140	2	94	96
160	2	95	97
180	2	97	99
200	2	98	100

PARTIAL PRESSURE 130

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	9	11
20	2	31	33
30	2	44	46
40	2	56	58
60	2	75	77
80	2	88	90
100	2	95	97
120	2	100	102
140	2	103	105
160	2	105	107
180	2	106	108
200	2	107	109
220	2	108	110

PARTIAL PRESSURE 140

Time of Dive	To 1st Stop	Feet and Minutes 50	Total Time
10	2	10	12
20	2	34	36
30	2	50	52
40	2	63	65
60	2	83	85
80	2	96	98
100	2	104	108
120	2	109	111
140	2	111	113
160	2	113	115
180	2	115	117
200	2	116	118
220	2	117	119

PARTIAL PRESSURE 150

Time of Dive	To 1st Stop	Feet and 60	Minutes 50	Total Time
10	3	0	10	13
20	3	0	36	39
30	3	0	56	59
40	3	10	61	74
60	3	10	81	94
80	3	10	94	107
100	3	10	101	114
120	3	10	106	119
140	3	10	109	122
160	3	10	111	124
180	3	10	113	126
200	3	10	114	127
220	3	10	114	127
240	3	10	115	128

PARTIAL PRESSURE 160

Time of Dive	To 1st Stop	Feet and 60	Minutes 50	Total Time
10	3	0	21	24
20	3	10	34	42
30	3	10	54	67
40	3	10	69	82
60	3	10	91	104
80	3	10	102	115
100	3	10	108	121
120	3	10	113	126
140	3	10	115	128
160	3	10	116	129
180	3	10	117	130
200	3	12	117	132
220	3	14	117	134
240	3	15	117	135

PARTIAL PRESSURE 170

Time of Dive	To 1st Stop	Feet 70	and 60	Minutes 50	Total Time
10	3	0	10	16	29
20	3	0	10	38	51
30	3	0	10	61	74
40	3	0	10	75	88
60	3	7	10	94	114
80	3	7	10	106	126
100	3	7	10	113	133
120	3	7	10	117	137
140	3	8	13	117	141
160	3	10	14	117	144
180	3	12	15	117	147
200	3	13	15	117	148
220	3	14	15	117	149
240	3	15	15	117	150

PARTIAL PRESSURE 180

Time of Dive	To 1st Stop	Feet 80	and 70	Minutes 60	50	Total Time
10	3	0	7	10	19	39
20	3	0	7	10	43	63
30	3	0	7	10	64	84
40	3	0	7	10	80	100
60	3	0	7	10	101	121
80	3	0	9	10	110	132
100	3	7	5	12	117	144
120	3	7	9	13	117	149
140	3	7	11	14	117	152
160	3	7	14	15	117	156
180	3	7	17	15	117	159
200	3	7	19	15	117	161
220	3	7	21	15	117	163
240	3	7	23	15	117	165

PARTIAL PRESSURE 190

Time of Dive	To 1st Stop	80	70	60	50	Total Time
		Feet and Minutes				
10	4	0	7	10	21	42
20	4	0	7	10	49	70
30	4	0	7	10	70	91
40	4	7	0	10	87	108
60	4	7	5	10	103	129
80	4	7	9	10	115	145
100	4	7	13	11	117	152
120	4	7	17	13	117	158
140	4	9	19	14	117	163
160	4	11	20	15	117	167
180	4	13	21	15	117	170
200	4	14	22	15	117	172
220	4	15	23	15	117	174
240	4	16	23	15	117	175

PARTIAL PRESSURE 200

Time of Dive	To 1st Stop	90	80	70	60	50	Total Time
		Feet and Minutes					
10	4	0	0	7	10	24	45
20	4	0	7	0	10	55	76
30	4	0	7	0	10	74	95
40	4	0	7	4	10	91	116
60	4	0	7	9	10	109	139
80	4	7	3	13	12	115	154
100	4	7	6	16	14	117	164
120	4	7	8	20	15	117	171
140	4	7	11	21	15	117	175
160	4	7	15	23	15	117	181
180	4	7	17	23	15	117	183
200	4	7	18	23	15	117	184
220	4	7	20	23	15	117	186
240	4	8	20	23	15	117	187

PARTIAL PRESSURE 210

Time of Dive	To 1st Stop	Feet and Minutes 90	80	70	60	50	Total Time
10	4	0	7	0	10	27	48
20	4	0	7	0	10	57	78
30	4	7	0	3	10	79	103
40	4	7	0	7	10	94	122
60	4	7	4	10	10	110	145
80	4	7	8	14	12	117	162
100	4	7	12	17	14	117	171
120	4	8	15	21	15	117	180
140	4	10	17	21	15	117	184
160	4	12	17	22	15	117	187
180	4	14	18	22	15	117	190
200	4	16	18	23	15	117	192
220	4	17	19	23	15	117	194
240	4	18	20	23	15	117	196

PARTIAL PRESSURE 220

Time of Dive	To 1st Stop	Feet and Minutes 100	90	80	70	60	50	Total Time
10	4	0	0	7	0	10	29	50
20	4	0	7	0	1	10	62	84
30	4	0	7	0	6	10	84	111
40	4	0	7	3	9	10	98	131
60	4	7	0	9	11	11	113	155
80	4	7	3	11	15	13	117	170
100	4	7	6	14	17	15	117	180
120	4	7	8	18	23	15	117	192
140	4	7	11	18	23	15	117	195
160	4	7	14	19	23	15	117	199
180	4	7	15	20	23	15	117	201
200	4	7	16	20	23	15	117	202
220	4	8	17	20	23	15	117	204
240	4	9	19	20	23	15	117	207

PARTIAL PRESSURE 230

Time of Dive	To 1st Stop	110	100	Feet and Minutes 90	80	70	60	50	Total Time
10	4	0	0	0	7	0	10	31	52
20	4	0	0	7	0	3	10	66	90
30	4	0	0	7	2	4	10	87	116
40	4	0	7	0	6	9	10	102	138
60	4	0	7	4	9	12	11	114	161
80	4	0	7	8	12	17	14	117	183
100	4	0	7	12	15	20	15	117	194
120	4	0	8	14	19	23	15	117	204
140	4	0	10	16	20	23	15	117	209
160	4	7	6	18	20	23	15	117	214
180	4	7	7	19	20	23	15	117	216
200	4	7	9	19	20	23	15	117	218
220	4	7	11	19	20	23	15	117	220
240	4	7	13	19	20	23	15	117	222

PARTIAL PRESSURE 240

Time of Dive	To 1st Stop	110	100	Feet and Minutes 90	80	70	60	50	Total Time
10	4	0	0	7	0	0	10	35	56
20	4	0	7	0	1	4	10	71	97
30	4	0	7	0	5	7	10	90	123
40	4	7	0	3	7	9	10	103	143
60	4	7	0	8	10	14	11	115	169
80	4	7	3	10	14	18	14	117	187
100	4	7	6	12	17	23	15	117	201
120	4	7	7	16	19	23	15	117	208
140	4	7	11	16	20	23	15	117	213
160	4	7	13	19	20	23	15	117	218
180	4	8	15	19	20	23	15	117	221
200	4	8	17	19	20	23	15	117	223
220	4	9	17	19	20	23	15	117	224
240	4	11	17	19	20	23	15	117	226

PARTIAL PRESSURE 250

Time of Dive	To 1st Stop	120	110	100	90	80	70	60	50	Total Time
		Feet	and	Minutes						
10	4	0	0	7	0	0	1	10	38	60
20	4	0	0	7	0	1	6	10	73	101
30	4	0	7	0	4	6	8	10	95	132
40	4	0	7	3	5	8	9	10	106	149
60	4	0	7	4	8	11	14	12	117	177
80	4	0	7	7	11	16	18	15	117	195
100	4	0	7	10	14	19	23	15	117	209
120	4	7	3	12	17	19	23	15	117	217
140	4	7	4	15	18	19	23	15	117	222
160	4	7	7	16	19	19	23	15	117	227
180	4	7	9	17	19	20	23	15	117	231
200	4	7	11	17	19	20	23	15	117	233
220	4	7	12	17	19	20	23	15	117	234
240	4	7	13	17	19	20	23	15	117	235

PARTIAL PRESSURE 260

Time of Dive	To 1st Stop	120	110	100	90	80	70	60	50	Total Time
10	4	0	0	7	0	0	2	10	41	64
20	4	0	7	0	0	3	7	10	77	105
30	4	0	7	0	4	6	8	10	97	136
40	4	0	7	2	5	9	9	10	109	155
60	4	7	0	7	9	12	16	13	116	184
80	4	7	3	9	13	15	21	15	117	204
100	4	7	6	11	14	19	23	15	117	218
120	4	7	8	13	19	20	23	15	117	226
140	4	7	11	15	19	20	23	15	117	231
160	4	8	13	17	19	20	23	15	117	236
180	4	9	14	17	19	20	23	15	117	238
200	4	10	16	17	19	20	23	15	117	241
220	4	11	16	17	19	20	23	15	117	242
240	4	13	16	17	19	20	23	15	117	244

PARTIAL PRESSURE 270

Time of Dive	To 1st Stop	130	120	110	100	90	80	70	60	50	Total Time
		Feet and Minutes									
*10	4	0	0	7	0	0	0	4	10	44	70
20	4	0	0	7	0	2	4	6	10	80	113
30	4	0	7	0	2	5	6	9	10	100	143
40	4	0	7	0	3	8	9	10	10	110	161
60	4	0	7	3	7	10	14	16	13	117	191
80	4	0	7	6	10	13	17	23	15	117	212
100	4	7	2	9	13	16	20	23	15	117	226
120	4	7	4	11	14	19	20	23	15	117	234
140	4	7	5	14	15	19	20	23	15	117	239
160	4	7	7	15	17	19	20	23	15	117	244
180	4	7	9	16	17	19	20	23	15	117	247
200	4	7	11	16	17	19	20	23	15	117	249
220	4	7	13	16	17	19	20	23	15	117	251
240	4	7	15	16	17	19	20	23	15	117	253

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 280

Time of Dive	To 1st Stop	130	120	110	100	90	80	70	60	50	Total Time
		Feet and Minutes									
*10	4	0	0	7	0	0	1	3	10	47	73
20	4	0	7	0	0	2	6	6	10	84	119
30	4	0	7	0	3	6	6	9	10	104	149
40	4	7	0	2	5	8	8	12	11	113	170
60	4	7	0	6	8	10	14	18	14	116	197
80	4	7	3	8	11	14	17	23	15	117	219
100	4	7	5	11	13	16	20	23	15	117	231
120	4	7	8	12	16	19	20	23	15	117	241
140	4	7	10	16	17	19	20	23	15	117	248
160	4	8	13	16	17	19	20	23	15	117	252
180	4	9	14	16	17	19	20	23	15	117	254
200	4	10	15	16	17	19	20	23	15	117	256
220	4	12	15	16	17	19	20	23	15	117	258
240	4	14	15	16	17	19	20	23	15	117	260

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 290

Time of Dive	To 1st Stop	140	130	120	110	100	90	80	70	60	50	Total Time
					Feet	and	Minutes					
*10	4	0	0	0	7	0	0	2	3	10	49	76
20	4	0	0	7	0	0	4	6	7	10	86	124
30	4	0	7	0	1	5	5	9	9	10	105	155
40	4	0	7	0	4	6	8	9	12	11	114	175
60	4	0	7	4	6	8	12	15	18	14	117	205
80	4	7	0	7	9	11	15	17	23	15	117	225
100	4	7	2	9	11	15	17	20	23	15	117	240
120	4	7	4	11	13	16	19	20	23	15	117	249
140	4	7	5	13	16	17	19	20	23	15	117	256
160	4	7	8	14	16	17	19	20	23	15	117	260
180	4	7	10	15	16	17	19	20	23	15	117	263
200	4	7	12	15	16	17	19	20	23	15	117	265
220	4	7	13	15	16	17	19	20	23	15	117	266
240	4	7	14	15	16	17	19	20	23	15	117	267

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 300

Time of Dive	To 1st Stop	150	140	130	120	110	100	90	80	70	60	50	Total Time
*10	5	0	0	0	7	0	0	0	3	3	10	52	81
*20	5	0	0	7	0	0	1	6	6	6	10	91	133
30	5	0	0	7	0	2	5	5	9	9	10	106	158
40	5	0	0	7	0	5	7	8	11	13	12	111	179
60	5	0	7	0	6	7	9	12	15	20	15	117	213
80	5	0	7	2	8	10	12	16	19	23	15	117	234
100	5	0	7	5	10	12	15	19	20	23	15	117	248
120	5	0	7	8	11	16	17	19	20	23	15	117	258
140	5	0	8	9	14	16	17	19	20	23	15	117	263
160	5	0	8	13	15	16	17	19	20	23	15	117	268
180	5	7	3	13	15	16	17	19	20	23	15	117	270
200	5	7	5	14	15	16	17	19	20	23	15	117	273
220	5	7	6	14	15	16	17	19	20	23	15	117	274
240	5	7	9	14	15	16	17	19	20	23	15	117	277

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 310

Time of Dive	To 1st Stop	150	140	130	120	110	100	90	80	70	60	50	Total Time
					Feet	and	Minutes						
*10)	5	0	0	0	7	0	0	1	3	3	10	54	84
20	5	0	0	7	0	0	3	5	6	6	10	93	135
30	5	0	7	0	0	5	5	7	8	13	10	109	165
40	5	0	7	0	3	5	8	8	11	20	11	115	186
60	5	0	7	3	6	7	10	12	17	23	15	117	219
80	5	7	0	6	9	11	12	16	19	23	15	117	240
100	5	7	1	9	10	14	17	19	20	23	15	117	256
120	5	7	4	11	12	14	17	19	20	23	15	117	263
140	5	7	5	12	15	16	17	19	20	23	15	117	270
160	5	7	8	14	15	16	17	19	20	23	15	117	275
180	5	7	10	14	15	16	17	19	20	23	15	117	277
200	5	7	12	14	15	16	17	19	20	23	15	117	279
220	5	8	13	14	15	16	17	19	20	23	15	117	281
240	5	9	13	14	15	16	17	19	20	23	15	117	282

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 320

Time of Dive	To 1st Stop	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
					Feet	and	Minutes							
*10	5	0	0	0	7	0	0	0	2	3	3	10	57	88
*20	5	0	0	7	0	0	1	4	5	6	7	10	94	140
30	5	0	0	7	0	2	4	5	7	8	11	10	110	169
40	5	0	7	0	1	4	6	7	8	12	15	12	117	194
60	5	0	7	0	5	6	9	11	13	17	20	15	117	225
80	5	0	7	3	7	9	11	13	17	20	23	15	117	247
100	5	0	7	5	9	11	13	17	19	20	23	15	117	261
120	5	0	7	7	12	13	16	17	19	20	23	15	117	271
140	5	7	2	9	12	15	16	17	19	20	23	15	117	277
160	5	7	3	11	14	15	16	17	19	20	23	15	117	282
180	5	7	5	11	14	15	16	17	19	20	23	15	117	284
200	5	7	6	13	14	15	16	17	19	20	23	15	117	287
220	5	7	7	13	14	15	16	17	19	20	23	15	117	288
240	5	7	9	13	14	15	16	17	19	20	23	15	117	290

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 330

Time of Dive	To 1st Stop	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
		Feet and Minutes												
*10	5	0	0	0	7	0	0	0	3	3	3	10	60	92
20	5	0	0	7	0	0	2	5	5	6	8	10	96	144
30	5	0	7	0	0	4	4	6	7	9	11	11	112	176
40	5	0	7	0	4	4	6	7	9	12	16	14	114	198
60	5	7	0	2	6	8	9	11	14	17	23	15	117	234
80	5	7	0	6	8	8	13	14	19	20	23	15	117	255
100	5	7	3	7	10	11	16	17	19	20	23	15	117	271
120	5	7	4	9	12	13	16	17	19	20	23	15	117	277
140	5	7	6	11	13	15	16	17	19	20	23	15	117	282
160	5	7	8	11	14	15	16	17	19	20	23	15	117	287
180	5	7	10	13	14	15	16	17	19	20	23	15	117	289
200	5	7	12	13	14	15	16	17	19	20	23	15	117	291
220	5	9	12	13	14	15	16	17	19	20	23	15	117	293
240	5	10	12	13	14	15	16	17	19	20	23	15	117	294

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 340

Time of Dive	To 1st Stop	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
		Feet and Minutes													
*10	5	0	0	0	7	0	0	0	1	3	3	4	10	64	98
*20	5	0	0	7	0	0	1	3	4	6	5	10	10	98	150
30	5	0	0	7	0	1	4	5	6	8	8	13	11	113	181
40	5	0	7	0	1	4	5	7	7	10	12	17	13	117	205
60	5	0	7	0	5	6	8	9	11	15	19	23	15	117	240
80	5	0	7	2	7	8	10	13	15	19	20	23	15	117	261
100	5	0	7	5	9	9	13	16	17	19	20	23	15	117	275
120	5	7	1	7	10	13	15	16	17	19	20	23	15	117	285
140	5	7	2	9	12	14	15	16	17	19	20	23	15	117	291
160	5	7	4	10	13	14	15	16	17	19	20	23	15	117	295
180	5	7	5	12	13	14	15	16	17	19	20	23	15	117	298
200	5	7	6	12	13	14	15	16	17	19	20	23	15	117	299
220	5	7	8	12	13	14	15	16	17	19	20	23	15	117	301
240	5	7	10	12	13	14	15	16	17	19	20	23	15	117	303

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 350

Time of Dive	To 1st Stop	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
		Feet and Minutes													
*10	5	0	0	0	7	0	0	0	2	3	3	4	10	67	102
*20	5	0	0	7	0	0	1	4	5	7	8	9	10	99	156
30	5	0	7	0	0	3	5	5	6	8	9	13	10	115	186
40	5	0	7	0	2	4	6	7	8	10	13	16	14	117	209
60	5	7	0	3	5	6	9	10	13	16	18	19	15	117	243
80	5	7	0	7	7	8	11	13	15	19	20	23	15	117	267
100	5	7	2	8	8	12	13	16	17	19	20	23	15	117	282
120	5	7	4	9	11	13	15	16	17	19	20	23	15	117	291
140	5	7	6	11	13	14	15	16	17	19	20	23	15	117	298
160	5	7	9	11	13	14	15	16	17	19	20	23	15	117	301
180	5	8	9	12	13	14	15	16	17	19	20	23	15	117	303
200	5	8	11	12	13	14	15	16	17	19	20	23	15	117	305
220	5	10	11	12	13	14	15	16	17	19	20	23	15	117	307
240	5	11	11	12	13	14	15	16	17	19	20	23	15	117	308

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 360

Time of Dive	To 1st Stop	180	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
		Feet and Minutes														
*10	5	0	0	0	7	0	0	0	1	2	3	3	5	10	69	106
*20	5	0	0	7	0	0	0	3	4	5	5	7	9	10	102	158
30	5	0	0	7	0	1	4	4	5	7	8	11	13	11	114	190
40	5	0	7	0	1	3	5	6	7	8	11	14	17	15	117	216
60	5	0	7	0	5	5	8	8	11	12	16	19	23	15	117	251
80	5	0	7	2	7	7	10	11	13	[illegible]	19	20	23	15	117	273
100	5	7	0	6	8	9	11	15	[illegible]	[illegible]	19	20	23	15	11[illegible]	288
120	5	7	1	7	9	12	14	15	[illegible]	[illegible]	19	20	23	15	117	297
140	5	7	3	9	11	13	14	15	16	[illegible]	19	20	23	15	117	304
160	5	7	4	10	12	13	14	15	16	[illegible]	19	20	23	15	117	307
180	5	7	5	11	12	13	14	15	16	17	19	20	23	15	117	309
200	5	7	7	11	12	13	14	15	16	17	19	20	23	15	117	311
220	5	7	9	11	12	13	14	15	16	17	19	20	23	15	117	313
240	5	7	10	11	12	13	14	15	16	17	19	20	23	15	117	314

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 370

Time of Dive	To 1st Stop	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
*10	5	0	0	0	0	7	0	0	0	1	2	2	3	7	10	69	106
*20	5	0	0	0	7	0	0	1	3	4	5	5	8	10	10	104	162
30	5	0	0	7	0	0	3	3	5	6	7	8	11	12	14	117	198
40	5	0	0	7	0	2	4	5	7	7	9	10	14	19	15	117	221
60	5	0	0	7	2	5	6	7	9	11	14	16	19	23	15	117	256
80	5	0	7	0	6	6	8	11	12	14	16	19	20	23	15	117	279
100	5	0	7	2	7	8	11	13	13	16	17	19	20	23	15	117	293
120	5	0	7	4	8	10	12	14	15	16	17	19	20	23	15	117	302
140	5	7	0	7	9	12	13	14	15	16	17	19	20	23	15	117	309
160	5	7	0	9	10	12	13	14	15	16	17	19	20	23	15	117	312
180	5	7	2	9	11	12	13	14	15	16	17	19	20	23	15	117	315
200	5	7	3	10	11	12	13	14	15	16	17	19	20	23	15	117	317
220	5	7	5	10	11	12	13	14	15	16	17	19	20	23	15	117	319
240	5	7	7	10	11	12	13	14	15	16	17	19	20	23	15	117	321

Columns 190–50: Feet and Minutes

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 380

Time of Dive	To 1st Stop	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
*10	5	0	0	0	7	0	0	0	0	2	3	3	3	7	10	72	113
*20	5	0	0	7	0	0	0	2	4	4	5	5	8	10	10	105	166
*30	5	0	7	0	0	1	3	4	4	7	7	8	11	16	11	117	202
40	5	0	7	0	0	4	4	5	6	8	10	11	14	20	15	117	226
60	5	0	7	0	4	5	7	8	9	11	13	17	20	23	15	117	261
80	5	7	0	3	6	7	9	10	12	15	17	19	20	23	15	117	285
100	5	7	0	6	7	9	10	14	15	16	17	19	20	23	15	117	300
120	5	7	1	7	9	11	13	14	15	16	17	19	20	23	15	117	309
140	5	7	2	9	11	12	13	14	15	16	17	19	20	23	15	117	315
160	5	7	4	10	11	12	13	14	15	16	17	19	20	23	15	117	318
180	5	7	5	10	11	12	13	14	15	16	17	19	20	23	15	117	319
200	5	7	7	10	11	12	13	14	15	16	17	19	20	23	15	117	321
220	5	7	9	10	11	12	13	14	15	16	17	19	20	23	15	117	323
240	5	8	10	10	11	12	13	14	15	16	17	19	20	23	15	117	325

Columns 190–50: Feet and Minutes

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 390

Time of Dive	To 1st Stop	200	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
*10	5	0	0	0	0	7	0	0	0	0	2	3	3	4	7	10	74	116
*20	5	0	0	0	7	0	0	1	2	4	5	5	5	9	9	10	109	172
30	5	0	0	7	0	0	2	4	5	6	7	8	10	12	12	12	116	206
40	5	0	0	7	0	2	3	5	6	6	8	9	13	14	21	15	117	231
60	5	0	7	0	2	5	5	8	8	9	11	15	17	20	23	15	117	268
80	5	0	7	0	5	7	8	9	11	12	16	17	19	20	23	15	117	292
100	5	0	7	2	7	8	9	11	14	15	16	17	19	20	23	15	117	307
120	5	0	7	5	8	9	11	13	14	15	16	17	19	20	23	15	117	316
140	5	7	0	7	10	10	12	13	14	15	16	17	19	20	23	15	117	322
160	5	7	1	9	10	11	12	13	14	15	16	17	19	20	23	15	117	325
180	5	7	3	9	10	11	12	13	14	15	16	17	19	20	23	15	117	327
200	5	7	5	10	10	11	12	13	14	15	16	17	19	20	23	15	117	329
220	5	7	7	10	10	11	12	13	14	15	16	17	19	20	23	15	117	331
240	5	7	8	10	10	11	12	13	14	15	16	17	19	20	23	15	117	332

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 400

Time of Dive	To 1st Stop	210	200	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
*10	5	0	0	0	0	0	7	0	0	0	1	2	3	3	6	9	10	74	121
*20	5	0	0	0	7	0	0	0	1	4	4	4	5	8	8	10	10	109	176
*30	5	0	0	7	0	0	0	4	4	4	5	7	7	10	11	15	13	117	209
40	5	0	0	7	0	1	4	5	6	6	6	7	10	11	16	18	15	117	234
60	5	0	7	0	0	5	5	6	7	8	11	13	14	17	20	23	15	117	273
80	5	0	7	0	3	6	6	8	10	12	12	15	17	19	20	23	15	117	295
100	5	0	7	0	6	7	8	10	13	14	15	16	17	19	20	23	15	117	312
120	5	0	7	2	6	9	11	12	13	14	15	16	17	19	20	23	15	117	321
140	5	0	7	2	8	10	11	12	13	14	15	16	17	19	20	23	15	117	324
160	5	0	7	3	10	10	11	12	13	14	15	16	17	19	20	23	15	117	327
180	5	0	7	5	10	10	11	12	13	14	15	16	17	19	20	23	15	117	329
200	5	0	7	7	10	10	11	12	13	14	15	16	17	19	20	23	15	117	331
220	5	0	7	9	10	10	11	12	13	14	15	16	17	19	20	23	15	117	333
240	5	7	1	9	10	10	11	12	13	14	15	16	17	19	20	23	15	117	334

*Take 1 extra minute from 1st stop to next stop.

PARTIAL PRESSURE 410

Time of Dive	To 1st Stop	Feet and Minutes 210	200	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	Total Time
*10	5	0	0	0	0	7	0	0	0	0	2	2	3	3	6	9	10	78	126
*20	5	0	0	0	7	0	0	0	2	4	4	4	5	7	9	11	10	110	179
30	5	0	0	7	0	0	2	3	4	4	5	7	8	12	15	15	12	117	216
40	5	0	0	7	0	2	3	4	6	6	6	9	11	13	16	20	15	117	240
60	5	0	7	0	2	5	5	6	7	10	10	13	15	19	20	23	15	117	279
80	5	0	7	0	5	6	8	8	9	12	15	16	17	19	20	23	15	117	302
100	5	0	7	3	6	7	8	11	13	14	15	16	17	19	20	23	15	117	316
120	5	7	0	5	7	10	10	12	13	14	15	16	17	19	20	23	15	117	325
140	5	7	0	7	9	10	11	12	13	14	15	16	17	19	20	23	15	117	330
160	5	7	2	8	10	10	11	12	13	14	15	16	17	19	20	23	15	117	334
180	5	7	3	9	10	10	11	12	13	14	15	16	17	19	20	23	15	117	336
200	5	7	5	9	10	10	11	12	13	14	15	16	17	19	20	23	15	117	338
220	5	7	7	9	10	10	11	12	13	14	15	16	17	19	20	23	15	117	340
240	5	7	8	9	10	10	11	12	13	14	15	16	17	19	20	23	15	117	341

*Take 1 extra minute from 1st stop to next stop.

EMERGENCY TABLES FOR USING HELIUM-OXYGEN ONLY FOR DECOMPRESSION

In an emergency it may be that oxygen cannot be used for decompression, owing to failure of supply or possibly to oxygen symptoms due to excessive carbon dioxide. Either air or helium-oxygen may be used. Emergency tables for using helium-oxygen mixtures may be calculated for the particular dive being made. In order to have a table that may be immediately available, the decompression provided in regular tables should be given up to 60 feet and from that point on, this table should be used:

60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.
23 m.	26 m.	30 m.	35 m.	42 m.	55 m.

EMERGENCY TABLES FOR USING AIR FOLLOWING HELIUM-OXYGEN DIVE

In emergencies when it is not possible to use Helium-Oxygen Mixtures or oxygen during decompression it may become necessary to use air. Decompression for each case can be calculated. However, since the emergency may occur at any point from the bottom to the last stop, it seems impracticable to attempt to cover all of the possibilities in tables. Therefore, a table for maximum saturation is provided and this table may be used for any emergency. When it is possible to do so, the first twenty minutes of these tables, the air should be administered through the circulator. Otherwise the diver may experience uncomfortable symptoms, dizziness, weakness, etc.

The tables are provided for each fifty feet and the table selected should be the one next higher than the actual depth, unless the depth is at an even fifty foot figure.

-:TREATMENT TABLE:-

Depth	230	220	210	200	190	180	170	160	150	140	130	120	110	100	90	80	70	60	50	40	30	20	10	Total
100																				14	42	52	68	175
150																		22	30	35	42	52	68	249
200															7	22	24	26	30	35	42	52	68	306
250													13	18	19	22	24	26	30	35	42	52	68	351
300										4	14	16	16	18	19	22	24	26	30	35	42	52	68	387
350								9	13	13	15	16	17	18	20	22	24	27	30	35	42	52	68	421
400					3	11	12	12	13	14	15	16	17	18	20	22	24	27	30	35	42	52	68	451
450			6	10	11	11	12	12	13	14	15	16	17	18	20	22	24	27	30	35	42	52	68	475
500	9	9	10	10	11	11	12	12	13	14	15	16	17	18	20	22	24	27	30	35	42	52	68	497

(D)

INSTRUCTIONS FOR MIXING HELIUM AND OXYGEN FOR USE IN DIVING

Helium gas is kept in storage at the Naval Air Station, Lakehurst, N. J. It is obtained through the Bureau of Aeronautics. Requests are submitted to the Bureau of Construction and Repair for the number of cylinders required. Cylinders are charged to about 1800 pounds per square inch and they contain about 180 cubic feet of the gas at one atmosphere pressure. Whenever the term "cubic feet of gas used" appears it means the amount is at one atmosphere pressure. Precautions are taken to see that the helium cylinders and the gas are kept oil free because of the danger of explosion when oxygen is added if oil is present.

Helium fittings are made up with a left hand thread and special fittings must be made when using the cylinders.

Because of the high pressure in the cylinders when helium is received, an empty cylinder is attached to a full cylinder and the gas is allowed to equalize in the two cylinders. This step requires a fitting with two helium threaded nuts.

In order to add oxygen to the helium, a cylinder with pressure reduced as above is connected to an oxygen cylinder which contains gas at a pressure higher than that in the helium cylinder. This requires a fitting with one oxygen nut and one helium nut.

Both of the above fittings can be combined by using a cross shaped fitting having the four outlets, provided with two helium nuts, one oxygen nut and one pressure gauge (0-2000 pounds).

The percentage of oxygen to be added to the helium is obtained by determining the amount of increase of the pressure in the helium cylinder by the application of Boyle's Law. It requires some practice on the part of the gas mixer to be able to judge the temperature factors. Experience has shown that if the oxygen is allowed to enter the helium flask rapidly more accurate results are obtained. A fairly accurate thumb rule for mixing is to take the percentage of oxygen desired, add eleven, then multiply this percentage by the pressure in the helium cylinder which gives the amount of pressure to be added to the helium.

Gas should be mixed several days before it is to be used because the mixing of the gases is slow. Samples for analysis should not be drawn from the mixed cylinders until about 36 hours after mixing.

From Part I of the decompression tables it can be seen that there is considerable range of oxygen percentages for each depth. The greater the percentage, however, up to the limit for that depth, the less will be the decompression time required.

Therefore, extreme accuracy in the percentages obtained when mixing is not essential.

The analysis must be accurate to within one per cent and may be made by any standard gas analysis apparatus suitable for shipboard use.

Samples are obtained from the mixed cylinder by using a fitting of 1/4" high pressure tubing with a male helium thread and one end and a short section rubber tube on the other end. A "Hoke Needle Valve" is placed in the metal tube for controlling the amount of the sample. The threaded end is fitted to the cross fitting which is fitted to the cylinder. The rubber tube can then be fitted to a glass sample tube. Samples should be taken over mercury.

INSTRUCTIONS FOR USING HELIUM-OXYGEN GAS MIXTURES FOR DIVING

REVISED

The oxygen tension should not exceed 2.5 atmospheres. While it has been extablished that under ideal conditions a tension in excess of this can be breathed, the influence of CO_2 reduces the safe limit and it has been determimed that 2.5 atmospheres is safe under working conditions. Symptoms of excess oxygen may take the form of drowsiness, ringing of the ears, irritability and other emotional upsets, and should be reported promptly so that immediate steps can be taken to correct it. The reduction of the tension will give relief and may be accomplished by:

(a) Reducing the depth.
(b) Reducing the percentage of oxygen breathed.
(c) Reducing the CO_2 in the helmet by ventilating.

The maximum percentage permissable may be obtained as follows:

P equals $\frac{82.5}{D \text{ plus } 33}$ where D is actual depth of water.

Cylinders of mixed gas, in banks of five cylinders each, the oxygen percentages of which is within 2 per cent of each other, are attached to a manifold in such a way that each may be used for the divers' supply. A volume tank of about three (3) cubic feet capacity is attached to the manifold to take care of a sudden surge of demand and the divers' supply is taken from the volume tank.

The gas pressure is always kept at 50 pounds more than the pressure at the position of the diver. (over bottom pressure).

At the helmet the gas is admitted through an aspirator, the action of which is to partially circulate the gas in the helmet through a canister containing a carbon dioxide absorbent, Shell Natron. The gas supply, more than 3 cu.ft. per minute at 300 feet, is the driving force in the circulating system and also provide make up oxygen to the divers.

This gas supply is taken off the usual hose ahead of the control valve. It has a separate valve so that it can be closed off.

The control valve can be used at any time to ventilate the suit or to build up the pressure, for instance when decending.

The exhaust valve is kept closed when using the aspirator and the diver may have to operate the chin valve from time to time to keep from getting light.

In returning to the surface the gas is administered in the same manner as above during the decompression stages up to 60 feet. At this point pure oxygen is used. By ventilating twenty five (25) cubic feet of oxygen through the helmet, using the control valve, the helium oxygen gas is about eighty (80) per cent replaced by oxygen. The arrangement for using oxygen is similar to that described for helium-oxygen mixture.

When using the submersible decompression chamber, the suit is removed from the diver and either helium oxygen or oxygen is breathed through a mask.

SURFACE DECOMPRESSION PROCEDURE

The following surface decompression has been tried and proven satisfactory:

(a) In tables where first stop is 50 feet, allow diver to remain on oxygen for 10 minutes then surface diver and return him to 50 feet in the chamber as fast as possible and put him back on oxygen for the time as shown in the tables. EXAMPLE: Page 42, PP 110. Time of dive 20 mins. Bring diver to 50 feet in 2 minutes. Ventilate 25 cu.ft. of oxygen after arrival at 50 feet. Keep diver at 50 feet for 10 minutes. Bring diver to the surface and return him to 50 feet in the chamber and have him use an oxygen mask for 21 minutes at this depth.

(b) Where first stop is other than 50 feet, give decompression as listed until he arrives at the 50 foot stop then give him the same time at 50 feet as he has had at 60 feet. Surface him and return him to 50 feet in the chamber, giving him the time in the chamber as shown by the tables for his 50 foot stop. EXAMPLE: Page 50 PP 270. Time of dive 40 minutes. Give the diver the following decompression - 4 mins. to 120 feet, 7 minutes at 120 feet, 3 minutes at 100 ft., 8 minutes at 90 ft., 9 mins. at 80 ft., 10 mins. at 70 ft. Arrival at 60 feet shift to oxygen, ventilating for 25 cu.ft. and allow diver to remain there for 10 minutes as shown. Stop at 50 feet for 10 minutes. Bring diver to the surface and return him to 50 feet in the chamber and on oxygen for 110 minutes.

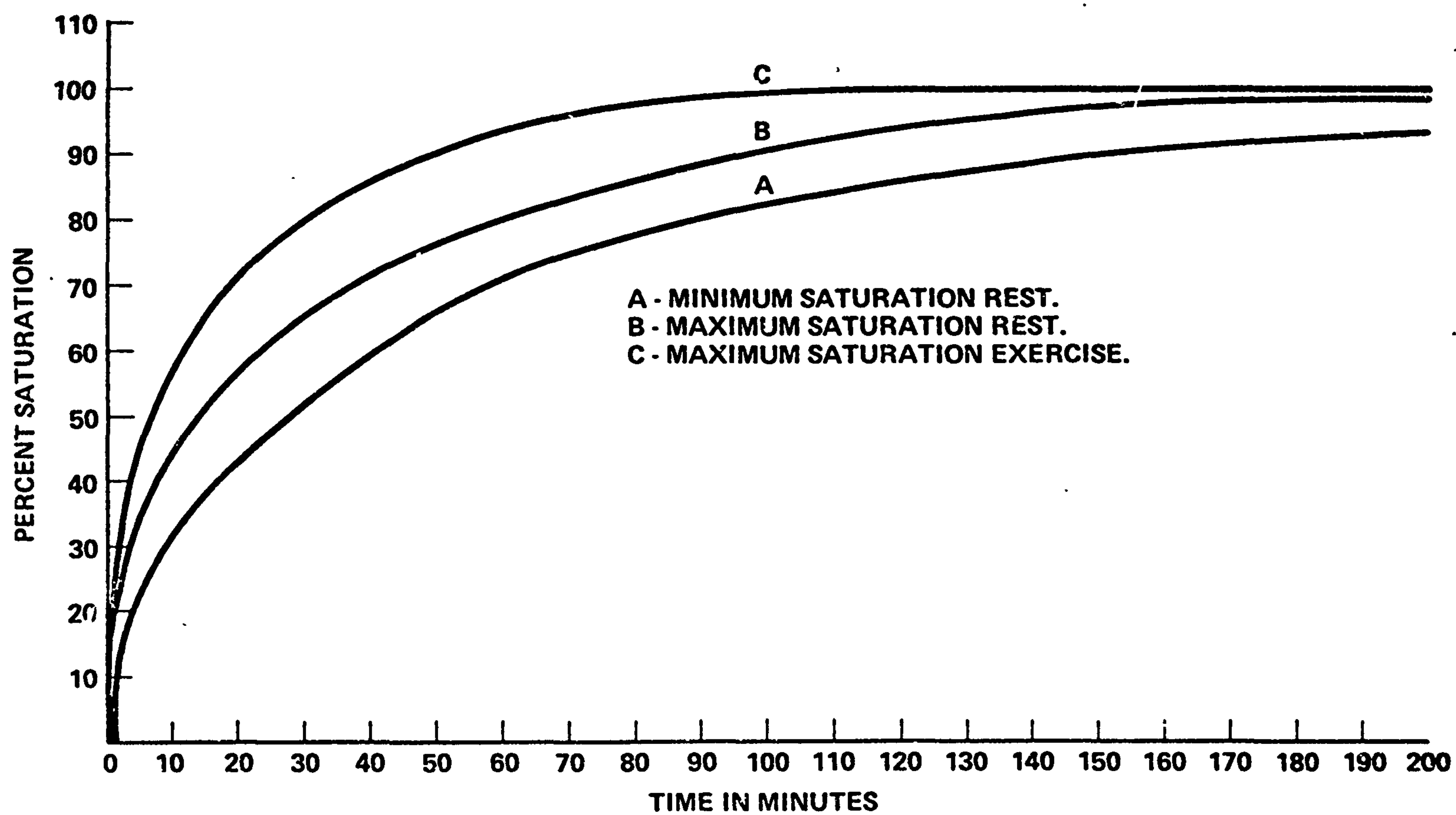
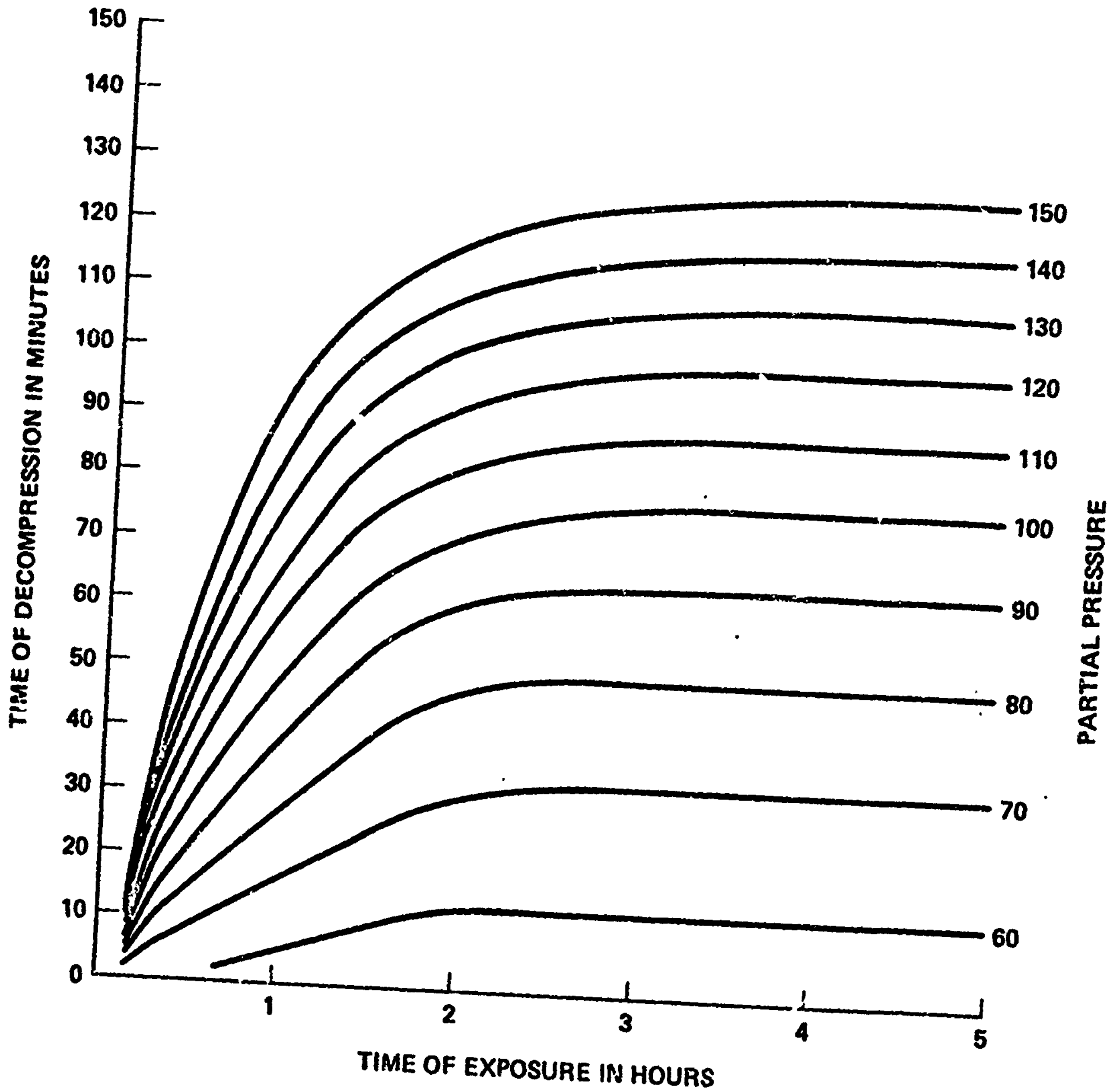


FIGURE 4.

HELIUM ELIMINATION BAND



OXYGEN DECOMPRESSION
FOR
HELIUM - OXYGEN DIVE

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(F) INFLUENCE OF EXERCISE ON DECOMPRESSION REQUIREMENTS

It is a well known fact that an increase in the circulatory rate of the blood stream will cause the body to absorb an increased amount of gas in a given time, when the body is exposed to a pressure greater than atmospheric. It is also well known that certain things produce an increase of circulatory rate in the body. Those things which might increase the rate in the diver's body are exercise, excitement, fear, breathing carbon dioxide etc. The amount of work etc. that a man can stand per minute decreases as the time factor increases.

For the purpose of determining the relation between work per minute and time, the world's record track times for all distances were plotted on cross section paper using feet per minute against time. This performance was considered to be the point of perfection for the perfectly trained human body.

The oxygen consumed by the body is in direct proportion to the foot pounds of work done during a given period.

By comparing the oxygen consumption of some of the world's greatest athletes while performing at their best, with the amounts consumed by Navy divers when working to a point just short of exhaustion it has been determined that the best that can be expected of the divers will be about 67 per cent of that of the perfect performance.

It followed that a curve, Figure 3, drawn parallel to the curve of perfect performance using 67 per cent of the feet per minute values, would represent amounts of work which might be expected from the Navy divers.

Using this curve as a basis, tasks were performed on an exercise bicycle while the men were breathing helium-oxygen mixtures. The amount of gas absored by the body was measured and checked against the amount absorbed when the men were at rest.

The percentages of increased saturation were obtained for various periods of work and it was found that the body absorbs, in any unit of time during which work to exhaustion is performed, an amount of gas approximately equal to the amount that would have been absorbed in two units of time, but at rest. This has been shown in Figure 4.

No one is able to judge what increase in circulation rate of the blood a diver experiences when he is in the water and for that reason the only safe decompression that can be provided is that which is based upon his having absorbed the maximum amount of gas during his period of exposure.

Therefore decompression tables that have been calculated for helium-oxygen diving are based upon the assumption that the diver has worked to exhaustion.

While it is admitted that under certain favorable conditions the decompression times may be reduced, to do so would cause the matter of complete decompression to enter a zone of probability.

It may be justified to take risks when the working conditions are such that excessive delays in operations are caused by having men in the water undergoing long periods of decompression, but when by using the submersible decompression chamber the divers can be removed from the water promptly, it appears that sound practice should dictate the use of tables that are safe beyond a doubt.

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PHYSIOLOGIC STUDIES OF HELIUM

By

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and

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Twenty years ago the cost of helium (2) was of the order of $2,500 per cubic foot. Its present volume production at a cost of 1 cent per cubic foot has made it available for the flotation of airships, for use in medical treatment, and for the prevention and treatment of compressed air illness.

In medicine Barach (3) began the study of the therapeutic use of helium particularly in the treatment of asthma and obstructive leisions of the larynx. More recently Eversole (4) tested its value in the field of inhalation anesthesia. The essential property making helium of value in these treatments is its decrease density compared with air.

In diving operations Sayers and Yant (5) suggested the breathing of helium because of its decreased solubility and more rapid diffusion rate. They showed that animals could be decompressed more rapidly in a He-02 atmosphere than in air. End (6) recently has experimented with helium in diving tests and his results are promising.

Some important properties of helium are its inactivity, since no compounds of helium are known to exist; its decreased density, one-seventh that of nitrogen; its rapid diffusion rate, twice that of nitrogen and its extremely low liquefying temperature, -267.9° C., or about 5.2° C. above absolute zero. In the following series of physiologic studies additional facts will be presented as they developed during an investigation connected with the use of helium in diving tests in depths up to 500 feet carried out at this diving unit under the supervision of Lieutenant Commander Momsen, U. S. Navy.

I - RELEVANT OBSERVATIONS OF THE EFFECTS OF HELIUM ON THE HUMAN BODY.

In the course of any extensive work with helium, investigators have invariably noticed several peculiar effects of this gas on the body. First, among these effects is the change in voice. The laryngeal muscles controlling as they do the tension of the vocal cords are trained from childhood to produce different tones. This muscular training, however, is accomplished in an air medium, the density of which is considerably greater than that of helium. Therefore, when an individual is breathing helium and attempts to talk the muscles respond as they normally do in air. The resulting sound is higher in pitch and nasal in quality compared with sound emitted when air is breathed. It is interesting to note that divers who have repeatedly breathed helium mixtures have overcome these voice phenomena somewhat so that the voice tone approaches normal.

Second among the bodily effects is a certain degree of chilling during the exposure to helium mixtures. This chilling was more noticeable during suit diving when in the water, although a lesser degree occurred during simple breathing under pressure in a dry chamber. It was thought that this chilling possibly might affect the required decompression time by slowing the circulation particularly in the skin area. Measures have been taken to warm the body during helium breathing, but there has not been sufficient time or experimentation to determine the effect on gas uptake, or gas elimination from the body.

With regard to bubble formation following exposure to high pressures it was reasonable to believe that gas emboli might form following helium breathing in a manner similar to their formation in an air atmosphere, if sufficient reduction in decompression time were made. This belief was substantiated by the occurrence of bends (7) while breathing or following the respiration of helium-oxygen mixtures. Certain differences, however, in the aspects of the cases of bends have been noted.

Preeminently there has been an absence of grave symptoms in a large number of cases. That is to say, symptoms such as unconsciousness and paralysis have not occurred. By contrast such mild symptoms as itching and skin rash have prevailed, frequently without sequellae. The occurrence of pain in about one-third of the cases has been promptly relieved by recompression and oxygen treatment.

To account for the absence of grave symptoms it should be noted that immediate treatment undoubtedly was an important factor, but, in addition, the low fat-water solubility ratio of helium compared with nitrogen is also an important consideration. Grave symptoms are usually produced when nervous tissue is the site of bubble formation. Such tissue having a high percentage of fat should absorb considerably less helium than nitrogen. Bearing in mind the low fat-water solubility ratio of helium, we have postulated further that in diving operations employing helium the important or controlling tissues concerned in decompression are those which are relatively rapid (tissues largely fluid) with regard to saturation or desaturation, whereas with nitrogen, the relatively slow or fatty tissues are all important.

This theory gleaned from the laboratory has been one of the fundamentals in formulating decompression tables for use with helium.

In connection with the treatment of bends it has been frequently observed that the bends respond more quickly to recompression and usually require less pressure for relief of symptoms than is required for the treatment of nitrogen bends.

Of all the bodily effects of helium the most striking is the feeling of normality, in contrast with the usual intoxication and sense of pressure and depth associated with high air pressures. This improved mental condition of the diver has supplanted the saving in decompression time as the most important expected advantage in using helium.

II - SOLUBILITY OF HELIUM IN WATER AND OLIVE OIL COMPARED WITH NITROGEN

The body solvents for inhaled gases are hemoglobin, fluids, and fat. Determinations of the solubility of helium in fat are of importance, therefore, in estimating the time necessary for the body to come into equilibrium with a constant helium tension in the lungs.

Since Campbell (8) has shown that the constituents of body fat, namely stearin, palmitin, and olein dissolve about the same amount of nitrogen per hundred cubic centimeters of substance as does bone marrow (90 per cent fat), or about 5 cubic centimeters of nitrogen per 100 cubic centimeters when saturated with air at 38° C., and approximately 6.6 cubic centimeters when the nitrogen tension is corrected to 760 millimeters; determinations of the solubility of helium in olive oil containing about 72 per cent olein and 28 per cent palmitin should give an accurate estimate of the solubility of helium in body fat.

Experimental Method

Olive oil, USP (9), was equilibrated at a temperature of 38° by bubbling through the oil pure nitrogen or helium (97.65 per cent) previously dried and freed from traces of carbon dioxide and oxygen by passage through sulphuric and pyrogallic acids for periods up to 1 1/2 hours.

The inert gas was then extracted in vacuo by repeated shaking in the Van Slyke apparatus.

The solubility of helium and nitrogen in water was determined under the same conditions except that the respective gases were passed through water in place of sulphuric acid before admission to the tonometer tube. The type of analytic procedure employed in these determinations was similar to that developed by Van Slyke and his co-workers (10).

Calculations

The volume per cent of gas in the analyzed solutions was calculated by means of equations formulated by Van Slyke and Stadie (11) for reducing the pressure of a gas extreacted in vacuo to standard conditions of temperature and pressure.

For water, the calculation simplified itself to -

Vol. per cent gas equals PxN2 factor.

For oil, i, the reabsorption coefficient, and a', the ostwald distribution coeffieient of a gas between gaseous and liquid phases, in the equation of Van Slyke and Stadie were omitted in the calculations since repeated gas extractions undoubtedly reduced these factors to a negligible minimum.

The helium in flasks was found by analysis to be 97.65 per cent pure. The residual gas was assumed to be nitrogen, and the necessary corrections were made in the calculations.

Discussion of Experimental Results

The analytical data are enumerated in table I. The solubility coefficient, a' represents the cubic centimeter of gas (0^{o}, 760 mm.) dissolved per cubic centimeter of liquid.

In the water analyses the greatest difference between the highest and lowest values was 0.01 volumes per cent, while in the oil analyses the greatest difference was 0.036 volumes per cent.

Our solubility value for nitrogen in water is only slightly higher than the usually accepted value (0.01272), (10) while the value for helium in water is 0.022 volumes per cent higher than the average reported by Hawkins and Shilling (12).

The following solubility ratios have been computed from the values in Table I:

Helium/Nitrogen in water	2 to 3
Helium/Nitrogen in oil	1 to 4.5
$\frac{\text{Helium in oil}}{\text{Helium in water}}$	1.7 to 1.
$\frac{\text{Nitrogen in oil}}{\text{Nitrogen in water}}$	5.24 to 1.

It is observed that the oil/water solubility ratio for helium is only one-third of the corresponding value for nitrogen.

FAT/BLOOD SOLUBILITY RATIOS FOR HELIUM & NITROGEN

The solubility of helium in blood (12) is about 1 per cent higher than our value for the solubility of helium in water. Since the solubility of nitrogen in blood (10) is also 1 to 2 per cent higher than the solubility of nitrogen in water, and since the solubility of the gases in oil is of the same degree as their respective solubility in body fat, it can be concluded that the fat/blood solubility ratio for helium is also only one-third of the corresponding ratio for nitrogen.

Application of Results

The comparatively low solubility of helium in fat is highly significant. Since fat and fatty tissue take up gas through the medium of the blood stream, this type of tissue governs the time required for the body as a whole to come into equilibrium with a given pulmonary gas tension.

With reference to nitrogen elimination from the body when oxygen is breathed, Behnke, Thomson, and Shaw (13) have pointed out that after the first hour the eliminated nitrogen comes mainly from fat and lipoid tissue. At the end of 6 hours nitrogen elimination had decreased to a value of about 7.5 cubic centimeters per hour. These measurements indicated that after 9 hours the body had lost 99 per cent of its nitrogen content.

Campbell and Hill (14) using an entirely different method of determining tissue saturation concluded that 12 hours or more would be required for complete desaturation.

On the basis of a blood/fat solubility ratio one-third that of nitrogen, helium should require from 3 to 5 hours for 99 per cent elimination measured after the body had previously been in equilibrium with a given pulmonary tension of this gas.

The Helium Content of the Body

In a man weighing 60 kilograms the water content may be estimated at 70 per cent or 42 kilograms, and the fat content at 13.2 per cent or 7.92 kilograms. The helium content of the body at atmospheric pressure (helium tension in the lungs, 570 millimeters) may then be computed in the following manner:

	Cubic Centimeters
0.00654 (a, H2O, 570 mm.) x 42,000	273
0.0111 (a, fat, 570 mm) x 8,800 (corr. for SG)	98
Body Total	373

In a man weighing 60 kilograms the nitrogen content was found to be 840 cubic centimeters (13). The helium content should be, therefore, about 45 per cent gas tension is the same in the lungs.

Possibility of Spinal Cord Injury Following Decompression from a Helium-Oxygen Atmosphere.

Nitrogen emboli interrupting the blood supply to the theracic and lumbar areas of the spinal cord produce the gravest complications of compressed air illness, namely, paralysis affecting the lower extremities, intestines, and genitourinary tract. Since the spinal cord consists of 27.5 per cent fat (13) a helium-oxygen mixture breathed in place of air should materially lessen damage to this vital tissue as a result of the comparatively low solubility coefficient of helium in fat.

SUMMARY

1. The solubility coefficients of helium in water and in oil have been determined and compared with the coefficients for nitrogen stand in the ratio of 2 to 3 for water and 1 to 4, 5 for oil, respectively. From these values the helium content of the body should be about 45 per cent as high as the nitrogen content when the same tension of each gas is breathed.

2. The decreased solubility of helium in fat compared with nitrogen should decrease the elimination time of this gas from the body and lessen the possibility of spinal cord injury.

TABLE I

Helium, Nitrogen solubility in water and in okive oil at 38°C.

WATER		OLIVE OIL	
a He	a N2	a He	a N2
0.00869	0.01274	0.01489	0.06689
0.00867	0.01269	0.01482	0.06653
0.00877	0.01273	0.01477	0.06668
0.00874	0.01283	0.01485	0.06669
		0.01467	0.06685
Average:			
0.00872	0.01275	0.0148	0.06673

III - MENTAL REACTIONS IN A HELIUM-OXYGEN ATMOSPHERE COMPARED WITH THOSE OCCURRING IN AIR

Behnke, Thompson, and Motley (15) first attributed the remarkable narcotic (intoxicating) effects of air at high pressures to the "atmospheric nitrogen" (16). It is worthy of note that although diving and caisson work had been in progress for a great many years, disturbances in motor control and behavior while occasionally recognized by alert diving officers (e.g. Saunders' report of the salvage of the S4) were described in the literature for the first time by Hill and Phillips in 1932 (17).

In regard to the manner in which nitrogen affects these disturbances it has been pointed out (15) that its action might be related to its high solubility coefficient in fat compared with water. Thus, an analogy could be drawn comparing nitrogen with the aliphatic anesthetics, the activity of which according to the Meyer-Overton law appeared to be related to their ratio of solubility in fat compared with water.

The practical conclusion drawn from these observations (15) was summarized by stating that - "An artificial gas mixture for divers is essential if operations at great depths (below 300 feet) are carried out *** such a mixture of course, should limit the oxygen concentration to that in the air at sea level, and in addition should provide a rapidly diffusible, sparingly soluble gas with a low partition coefficient."

The gas contemplated was helium but its cost at that time (1935) did not render it available for large scale diving operations. Improved methods of application made its use more practicable and 3 years later an opportunity was afforded at this unit to substitute a helium-oxygen atmosphere for air in depths up to 500 feet (16 atmospheres). It was possible, therefore, to test the belief that helium would free divers from the untoward effects of air (6) (15) and also to coroborate the finding that atmospheric nitrogen was responsible for these phenomena.

Essentially the helium-oxygen atmosphere abolishes, or renders negigible, the stupefaction and impaired motor control associated with air respiration under pressure. At a depth of 500 feet for example, the diver felt well and was conscious of being at a depth of not more than 100 feet. The sensation of pressure or depth by which experienced divers breathing air can estimate to within 50 feet the actual depth is uniformly absent in a helium-oxygen atmosphere.

In contrast to the feeling of normality experienced in the helium atmosphere at deep depths is the complete change brought about by replacement of helium with air, the oxygen concentration remaining constant. The sudden introduction of air at a depth of 300 feet to a diver breathing helium produced a sensation of "floating away", dizziness, and loss of muscular control, accompanied by an insistent demand to be brought to the surface. In effect the diver was experiencing the first stage of inhalation anesthesia.

It would be of some value, perhaps, if arithmetical tests could be used to evaluate the reactions associated with the respiration of various gases under pressure. Such test, however, are not practicable at the present time under our conditions of work. We have observed, for example, that arithmetical tests were of little value, since the effort and practice factors inherent in such tests rendered the interpretation of results difficult or invalid.

Since the air pressure disturbances are similar in many respects to those produced by alcohol, another narcotic substance, it seemed worth while to select a practical test of motor function from the carefully investigated field (18). It appeared that typewriting involving as it does a complex, continuous skilled act, would give data indicative of the manner in which a diver would perform his tasks under pressure. In this test the continuous performance renders subjective reinforcement (possible in intermittent tests such as marksmanship) difficult, or detectable by a slower rate of typewriting. The practice factor can also be eliminated by using skilled typists as subjects.

These data were obtained when a skilled typist breathed air and a helium-oxygen mixture alternately at various pressures, (depths) in a large steel chamber.

Surface	Air	He-02
Words per minute ---------	63.2	69
Errors per stroke ---------	0.0032	0.0052
200 feet.		
Words per minute ---------	53.0	63
Errors per stroke ---------	0.0135	0.005
250 feet		
Words per minute ---------	60.0	55.8
Errors per stroke ---------	0.011	0.0057

Comparable to the alcohol tests (18) are the clumsy mistakes made in the copy (whole sentence omitted at 250 ft.) greatly decreasing its legibility when air was breathed under pressure. Imparied judgement, a characteristic effect of high air pressure, is brought out by the fact that the typist realizing that he was making errors while breathing helium slowed down his rate of copy. Breathing air, on the other hand, gave him the feeling that he was doing exceptionally well and consequently he made no effort to decrease his speed.

Manner of Action of "Atmospheric Nitrogen" At High Pressures.

The low partition coefficient (fat/water solubility ratio) of helium (1.7 to 1) in contrast with nitrogen (5.24 to 1), and the comparative freedom from pressure effects when helium is breathed, give us a working hypothesis toward an understanding of the action of nitrogen discussed in a previous paper (15). While the nature of all narcotic activity is obscure, the relationship between narcotic potency of different alcohols and anesthetics and their relative fat and water solubilities as demonstrated by Meyer and Overton, may well apply to the narcotic action of gases. Specifically, an alteration brought about by the absorption or concentration of these fat solvent substances in the fatty components of the surface film of the nerve cell is thought to decrease cell membrane permeability with resulting narcotic effect (18).

Other differences between the two gases (argon should also be considered with nitrogen and is included in the term "Atmospheric N2") as an explanation of their opposite behavior may be related to the electronic inertness of the helium atom, depriving it of valence and the ability to combine with any known substance, in contrast with nitrogen which is electronically active, possesses valences of 3 and 5, and combines with many substances.

Limiting Depth When Helium is Breathed

The limiting depth when air is breathed may be placed at 300 to 350 feet. If its narcotic action is related to its partition coefficient, then helium with only one third the partition coefficient of nitrogen should enable divers (considering only the mental effects) to descent to a depth of about 1,000 feet.

Summary

In a helium-oxygen atmosphere the narcotic effects of "Atmospheric nitrogen" at corresponding high pressures are largely dispelled. The comparatively low fat/water solubility ratio of helium compared with nitrogen suggests the applicability of the Meyer-Overton law toward an understanding of the nature of nitrogen narcosis.

IV - HELIUM CONTENT OF THE BODY AND ITS RATE OF ELIMINATION.

Measurements of the rate of helium elimination from the body are essential for the calculation of decompression tables for divers.

Experimental Procedure

First class divers representing carefully selected and trained men whose ages ranged usually between 25 and 35 breathed a helium-oxygen mixture for periods averaging 3 1/2 hours either at atmospheric or increased barometric pressure. Following the period of helium respiration air or oxygen was rebreathed from a spirometer of the Benedict type. Analysis of spirometer gas for its helium content made possible the measurement of the body's helium content, and its rate of elimination.

Analysis of large samples of gas (500 cc) enabled us to measure quantities of helium as small as 1.5 cubic centimeters eliminated from the body during a half-hour period of rebreathing, and to recover about 99 per cent of the body's helium content. For our purpose we considered helium elimination complete when less than 1.5 cubic centimeters were given up by the body during a half-hour period.

The gas mixture breathed by the divers contained 73-76 per cent helium, 5-7 per cent nitrogen, and 19 to 20 per cent oxygen

Analysis of Helium

Helium can be separated from other inert gases by a physical method based on its low liquefying temperature. In the Cady apparatus activated charcoal is used to absorb nitrogen and gases other than helium at the temperature of liquid air (-189°). By means of a high vacuum applied to the charcoal the helium can be extracted, and subsequently measured in a burette.

A spectrum tube serves to identify helium, or impurities in the system, and to determine the approximate concentration of helium gas.

Computation of Helium Tension in the Body

The helium tension in the body at the end of a 3 1/2 hour helium-oxygen exposure was computed from the helium content of the urine instead of the helium percentage (73-76) of the inspired gas.

After 90 minutes of helium-oxygen respiration the tension of helium in the urine is in equilibrium with the helium tension of the kidneys, arterial blood, and alveolar gas (see part IV). By analyzing a sample of urine voided after 90 minutes for its helium content, and equalibrating a portion of the same urine with pure helium, we can compute the tension of helium in the urine from the formula,

$$\text{Tension helium} = \frac{\text{helium content urine}}{\text{helium content equilibrated urine}} \times B-W$$

where B is the barometric pressure and W the tension of water vapor.

Table II

Helium Elimination from a Diver, age 29, weight 74 kilograms (162 pounds).
(The average initial helium tension in the body was 413 millimeters).

Time in Mins.	Helium Cubic centimeters	Per Cent of Total	Rate corresponds to a 50%* desaturation time in -- Mins	Time in Mins.	Helium Cubic centimeters	Per Cent of Total	Rate corresponds to a 50% desaturation time in --Mins
3	75	29.0	6.25	180	247	94.6	43.00
20	147	56.5	17.00	210	251	96.2	43.00
30	169	64.8	20.00	240	254	97.3	43.00
60	201	77.0	27.50	270	256.5	98.3	43.00
90	223	85.4	31.00	300	258.5	99.4	43.00
120	233	89.3	36.00	330	260.0	99.5	43.00
150	242	92.7	40.00				

*A tissue half desaturating in 43 minutes will be 99.5 per cent desaturated in 330 minutes. (7.7 time units)

Discussion of Results

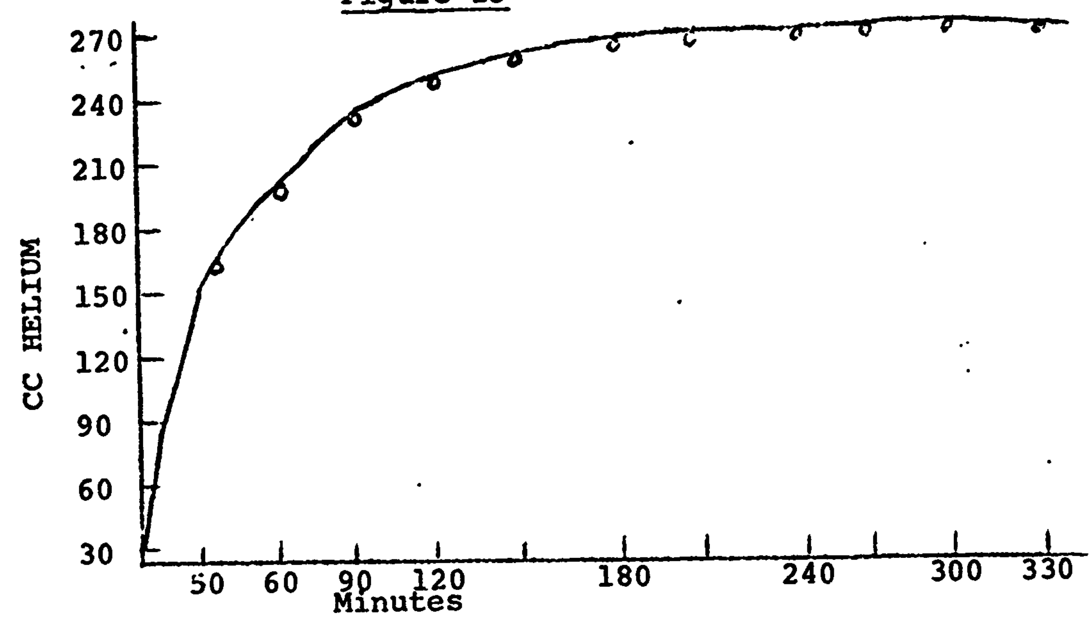
The graph (Fig. 15) represents the helium desaturation curve of a diver, age 29, weight 74 kilograms (162 pounds). The average helium tension in the body (urine) during the period of exposure in the helium-oxygen atmosphere was 413 millimeters.

In table II are listed the data applying to Fig. 15. The helium given up during the first 3 minutes (lung rinsing period) of oxygen breathing was estimated from values obtained for the third minute and from values computed from the product of cardiac output and the helium solubility coefficient in blood.

From these data we conclude that the quantity of helium dissolved in the tissues of men of the same weight is about 40 per cent of the nitrogen content (13) (19) for corresponding gas tensions in the body. The time required for helium elimination is about one-third to one-half the time required for nitrogen elimination (13) (14). The difficulty of measuring with precision the end point of nitrogen diffusion from the body in an oxygen atmosphere does not permit at this time a closer comparison of desaturation rate for the two gases.

The decreased total elimination time for helium as compared with nitrogen is roughly proportional to the blood and fat solubility ratios of the two gases (viz. part II). Essentially it is the high solvent capacity of body fat for nitrogen that delays the elimination of this gas (13). On the other hand, 50 per cent desaturation time in contrast with total elimination time is about the same (20 minutes) for each gas. During this first 20 minute period gas elimination is taking place from body fluids.

Figure 15



Possible Error from the Absorption of Helium in the Intestinal Tract

The question may arise as to whether the small quantities of helium eliminated after fourth hour are given up by the tissues or alimentary tract (20). Gas in the alimentary tract is mostly nitrogen, residual of swallowed air. When helium is breathed its entrance into the stomach and intestines occurs either by swallowing the gas or through diffusion from the blood stream. It is of interest to record that at one time experimental diving with helium was practically discontinued because the use of a mouthpiece for helium respiration resulted in swallowing large quantities of gas. During decompression the rapid expansion of the trapped gas caused intense, griping pains, and in addition created the possibility of gastric rupture.

To eliminate this source of error a test was conducted in which 500 cubic centimeters of helium were admitted to the small intestine through a Rehfuss tube. A roentgenogram of the abdomen taken a half hour later revealed the gas distributed throughout the large bowel. Three and one-half hours later about 4.4 cubic centimeters of helium were recovered from air rebreathed in a spirometer during a half-hour period. While these quantities of gas would undoubtedly affect a precise determination of helium diffusion from tissues, it was doubtful whether or not such large quantities of gas would be normally retained. In a second experiment 200 cubic centimeters of helium were introduced into the small bowel. Between the fourth and fifth hour after the introduction of gas only 1.6 cubic centimeters were eliminated from the lungs.

These tests showed that under ordinary conditions helium either swallowed or diffusing into the intestinal tract during saturation will not introduce significant error in measurements of helium elimination.

Summary

1. The helium content of the body is about 40 per cent of the nitrogen content for corresponding gas tensions.
2. At atmospheric pressure 99 per cent of the helium content is eliminated in five and one-half hours or in about one-half the time required for nitrogen desaturation.

V - THE NITROGEN OR HELIUM CONTENT OF THE URINE AS A TEST FOR BUBBLE FORMATION IN THE BLOOD STREAM.

Asimple test heretofore has not been available for estimating the efficiency of a given decompression schedule in promoting the elimination of excess gas from the tissues of the body without bubble formation.

Periodic measurements of inert gas content of the urine provide a simple and effective test for detecting the presence of excess gas held in supersaturation or bubble form in the blood stream.

Leonard Hill (21) in 1907 made analyses of the gaseous nitrogen content of urine to determine the time necessary for kidney saturation. Subsequent investigators, however, have not continued Hill's work, nor have they applied the principle underlying the urine analysis method to the problem under consideration.

Method of Procedure

Urine from divers exposed to a helium-oxygen atmosphere under pressure and air during decompression, was collected before a dive (control sample), immediately after surfacing, and then at hourly intervals until equilibrium was again established between the inert gas tension in urine and lungs.

The manner of urine analysis was essentially the same as the technique used by Van Slyke and his co-workers in their nitrogen solubility studies (10).

Since the solvent capacity of urine is decreased by the presence of dis-olved salts it was necessary to equilibrate a portion of each sample by bubbling air through the urine for 15 minutes at a temperature of 38°.

The difference between the gas content of immediately analyzed urine and the equilibrated portion denoted gas held in supersaturation.

Principles Underlying the Experimental Results

A condition of equilibrium through the media of arterial blood and kidneys is assumed to exist between the inert gas tension in urine and lungs at constant barometric pressure. Disturbance of this equilibrium is effected when a diver is subjected to increased pressure by diffusion of gas from the lungs into arterial blood, kidneys, and urine. With the subsequent release of pressure, diffusion in the reverse direction occurs until equilibrium is again restored.

The time required for the reestablishment of inert gas equilibrium between urine and lungs will be delayed if gas bubbles are present in the blood, especially in the arterial blood circulating through the kidneys. That bubbles of gas circulate in arterial blood in the early stages of compressed air illness (bends) has been observed by Behnke and Shaw (22).

In this paper experimental data will be presented in support of these statements.

Discussion of Experimental Results

Inert gas (nitrogen) content difference between bladder urine and equilibrated urine at atmospheric pressure. In 76 analyses the inert gas content of bladder urine was found to average 0.015 volumes per cent higher than the gas content of urine through which air was bubbled for 15 minutes. The greatest difference was 0.039 volumes per cent. In 8 analyses the gas content of bladder urine was slightly lower (from 0.006

to 0.016 volumes per cent) than the gas content of equilibrated urine.

Inert gas (nitrogen) content difference at increased pressure - At 2.2 atmospheres pressure the same difference or 0.015 volumes per cent, was found to occur between bladder urine in equilibrium with lung air and urine equilibrated with air at the same pressure.

Barometric pressure changes in relation to equilibrium time. - Between 30 and 60 minutes was required for the establishment of equilibrium (saturation) between the pulmonary and urinary gas tensions when the barometric pressure was raised; that is, in a pressure chamber or diving suit.

When the excess pressure is lowered to normal the same time is required for the restoration of gaseous equilibrium (desaturation), provided that the excess pressure is not too high (above 7.5 pounds) or the return to normal too abrupt. Desaturation time is prolonged by rapid decompression from higher pressures. This delay is undoubtedly the result of increased nitrogen tension in the arterial blood reaching the kidneys and is possibly indicative of gas embolism.

Variation of inert gas content in the lungs in relation to the excess gas content in the urine. - In table 3, values are given for the excess inert gas in urine for periods up to 4 hours following the decompression of divers from a depth of 225 feet. On the bottom the divers breathed a helium-oxygen mixture and, during decompression, air. It is observed that the higher inert gas tension in the lungs is reflected in higher urinary gas contents.

Excess gas content in the urine in relation to bubble formation in the blood (bends). - In Table 4, data are presented showing the relationship between the gas content of the urine and the occurrence of bends. The divers breathed a helium-oxygen mixture on the bottom and air during and following decompression. The control values in column 3 were obtained by analysis of urine voided immediately before a dive. Immediately following a dive the bladder was again emptied. The values in columns 1, 2 and 3 thus represented analyses of urine voided at the end of the first, 2nd, and 3rd hours, respectively. In these specimens, with one exception, helium could not be detected by our analytical methods.

We have come to regard the gas content values of the second hour (column 5) as of great improtance since under the system of decompression employed, high values were associated with the development of bends while normal values (below 0.04 volumes per cent) were obtained on divers who remained free from symptoms. In only one instance did bends occur following a normal 2 hour gas content value.

On the other hand, high 2 hour values may not be followed by bends. Thus, diver Z.A.M., who up to date has been immune to bends, showed high values during the second and third hours. However M.A.C., who on the following day was subjected to the same diving conditions, developed severe bends.

Some factor apparently enables certain individuals to hold gas in supersaturation in the blood, or if bubbles form, the blood flow, as a result of increased heart action or abundant collateral circulation, is sufficient to maintain adequate tissue nutrition. In this connection, End (6) has called attention to the association of bends and the presence of high concentrations of carbon dioxide in caissons as reported in the literature. At this unit Lieutenant Commander Momsen has had an opportunity to make tests on two occasions in which a high carbon dioxide content in the diver's gas mixture was followed by the development of bends. In control tests duplicating the conditions of the previous dives except for a lowered carbon dioxide tension in the inhaled gas mixture, the divers remained in excellent condition.

That the body can tolerate gas bubbles in the blood stream is indicated by the inert gas values for the first and second hours obtained on BUG. This excess gas was found on analysis to be helium, the only instance in which we have been able to detect helium in the urine 1 hour after decompression and about 2 1/2 after exposure in a helium-oxygen atmosphere. The existence of helium in bubble form in the blood is our only explanation for the prolonged presence of helium in the urine.

Further evidence of the presence of bubbles in blood associated with minor, and frequently prodromal symptoms of bends are brought out in tests involving a 2 minute return to normal pressure after a 30 minute exposure to a pressure of 4 atmospheres. Transient sequallae of such tests are skin itch and petechial rash indicative of bubbles in the cutaneous vessels. In explanation of this phenomenon it appears that gas in supersaturation is trapped in the skin vessels as a result of vasoconstriction brought about by the chilling cold associated with rapid decompression in a chamber. Subsequently with an increasing differential pressure the gas in supersaturation is released in the form of bubbles.

Diffusion of Helium Through the Bladder Wall - An important consideration in any study of urinary gas content is diffusion of gas through the bladder wall when the urinary gas tension is higher than the gas tension in the blood. During exposure in a high pressure helium-oxygen atmosphere the tension of helium in urine approaches equilibrium with the helium tension in the lungs. During decompression, however, the bladder urine loses about nine-tenths of its estimated helium content. This loss of helium undoubtedly takes place by diffusion through the bladder wall. The fugacity of helium is also greater in a distended bladder because, presumably, the stretched wall allows the gas to diffuse from urine more rapidly into the blood where the tension of helium is lower.

In an experiment designed to measure helium loss from retained bladder urine, 153 cubic centimeters of normal saline saturated with 1.63 volumes per cent helium at two atmospheres pressure were introduced by catheter into the bladder. Three hours later the voided urine-saline mixture contained a helium content of only 0.07 volumes per cent. Making allowance for the dilution of saline by secreted urine, it was computed that nine-tenths of the original content of helium had diffused into the blood stream through the bladder wall.

Summary

Periodic measurements of the inert gas content of the urine provide a simple and effective test for detecting the presence of excess gas held in supersaturation or in bubble form following the release of divers from high pressure atmospheres. By means of this test a quantitative estimate of gas elimination from the body can be obtained, and the occurrence of bends frequently can be prognosticated.

Data are presented indicating that helium diffuses through the bladder wall.

TABLE 3

The 225 foot Dives, 20 Minutes Duration, Diver Breathing Helium-Oxygen Mixture on the Bottom.

Diver	Date	Excess inert gas in urine (Volumes per cent)				Oxygen percentage in helmet on bot	Remarks
		1hr.	2 hrs.	3 hrs.	4 hrs.		
M.A.C.	3/24	.186	.049	.042	.013	12.8	
	3/25	.128	.035	.029	.013	21.1	
C.O.T.	3/24	.266	.044	.031	----	11.5	
	3/23	.080	.009	.003	----	20.6	
D.U.N.	3/22	.134	.007	----	----	12.8	
	3/24	.122	.002	----	----	22.9	

TABLE 3. (Cont'd)

Diver	Date	Excess inert gas in urine (Volumes per cent) 1 hr.	2 hrs.	3 hrs.	4 hrs.	OXYGEN percentage in helmet on bot	Remarks
T.H.O.	3/22	.132	.004	47 min	decomp	12.8	
	3/25	.115	.020	42 min	decomp	21.7	
	3/23	.105	.001	47 min	decomp	21.0	
M.E.T.	3/28	.312	.044	.001	.01	9.8	
	3/29	.104	.043	.009	----	21.4	Itch 1,
F.O.R.	3/23	.125	.031	.012	----	12.0	rash 1,
	3/22	.110	.032	.021	----	21.0	fatigue 2
F.R.Y.	3/28	.149	.050	.001	.021	10.0	

1 - Indicative of Bubbles in blood vessels of skin.
2 - Frequent precursor of bends.

TABLE 4

Excess Inert Gas in Urine in Relation to the Occurrence of Bends

Diver	DEPTH (Feet) (1)	Time on Bot (2)	Excess inert gas in urine (Volumes per cent) Control (3)	1 hr. (4)	2 hrs. (5)	3 hrs. (6)	Remarks
C.R.I.	350	20	.018	.11	.05	.017	Bends
R.I.E.	350	20	.000	.05	.028	.017	No symptoms
D.U.N.	400	20	.004	.099	.048	.041	Bends
M.E.T.	400	20	----	.13	.012	----	No symptoms
O.K.E.	400	18	----	----	.111	----	Bends
C.R.O.	400	18	.004	.18	.021	----	No symptoms
B.U.G.	375	20	.032	.20	.073	----	Bends
F.R.Y.	225	20	.029	.15	.05	.001	Mild Bends
M.E.T.	225	20	.015	.312	.044	.001	No symptoms
B.U.G.	300	20	.009	*.51	.35	----	Cold duringdiv
C.R.O.	350	20	.015	.14	.077	.005	Delayed bends
Z.A.M.	350	20	----	.17	.056	.051	No symptoms
M.A.C.	350	20	----	----	----	----	Bends

*Excess gas was helium.

(1) - From the Experimental Diving Unit, Navy Yard, Washington, D.C. The authors wish to express their appreciation to Lieut. Comdr. C. B. Momsen, USN, for many valuable suggestions, and to members of the Bureau of Construction and Repair for the splendid support that they have given to these investigations.
The technical work of L. B. Lewis, Pharmacist's mate first class, T. Merritt, Pharmacist's mate first class, and H. H. Snider, Pharmacist's mate third class, was especially commendable.

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