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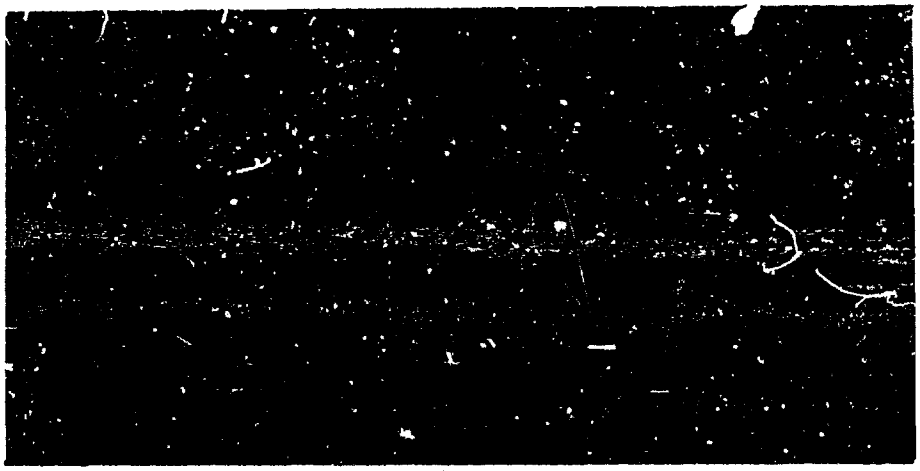

U. S. NAVY EXPERIMENTAL DIVING UNIT

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RESEARCH REPORT 6-65

CALCULATION OF DECOMPRESSION

SCHEDULES FOR NITROGEN—OXYGEN
AND HELIUM—OXYGEN DIVES.

PROJECT NO. SF-011-06-05

TASK NO. 11514, SUBTASK 5

BY

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ABSTRACT

This report presents the theoretical basis for calculation of decompression schedules for nitrogen-oxygen and helium-oxygen mixtures used in diving. It includes definitions, theory of exponential saturation and desaturation, and theory of limiting values of excess saturation permitted at various ambient pressures with helium and nitrogen. An attempt has been made to simplify the presentation of the calculation procedure to implement the theoretical method. The necessary tables and worksheets used in calculations are presented, together with sample calculations of dive schedules. The discussion describes and appraises other methods of calculation developed in recent years.

SUMMARY

PROBLEM

(1) Revise the Haldane method for the calculation of air decompression tables to a general case to be used for calculation of schedules for various nitrogen-oxygen and helium-oxygen mixture dives.

(2) Present developments in decompression theory subsequent to the Dwyer report (Experimental Diving Unit Research Report 4-56) which have a bearing on the calculation procedure.

FINDINGS

(1) This report presents a general case for calculation of decompression schedules for dives in which nitrogen-oxygen and helium-oxygen mixtures are breathed.

(2) The present status of decompression calculation procedures is discussed to include definitions and basic theories.

RECOMMENDATIONS

(1) Use this report for instruction in calculation procedures of decompression schedules.

(2) Revise the report or supercede it as a text when this is required.

FOREWORD

The procedure for calculation of decompression schedules given in this report is not new. It is based primarily on a method developed by Boycott, Damant and Haldane in 1908, further delineated by Yarbrough in 1937 and presented in a detailed report by Dwyer in 1956 as U. S. Navy Experimental Diving Unit Research Report 4-56 entitled "Calculation of Air Decompression Tables". The latter report presented a step-by-step procedure to be used in computer programing, and to serve also as a text for instruction of students, as amplified by exposition of the basic theories. With further development of limits of maximum tissue pressures at the various decompression stops, the standard air decompression tables, exceptional exposure tables and repetitive dive tables were calculated by this method. More recently, helium-oxygen decompression tables for mixed-gas SCUBA have also been developed by this method, employing control values for helium which differ from those for air.

Since decompression calculations must be used for dive schedules employing helium-oxygen, and nitrogen-oxygen mixtures other than air, it was considered important to present the modifications to the basic method required, as well as the control values limiting the tissue tensions of the various gases at the decompression stops. Aspects of decompression theory which have developed subsequent to the Dwyer report are discussed, as are other calculation procedures based on a diffusion-limited gas exchange model.

This is an interim report. Future reports will cover test dive results of schedules developed by this basic method.

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1. OBJECT

1.1 Objectives

(1) To detail the development of decompression calculation theory to include the method of Haldane and subsequently developed whole body gas exchange methods.

(2) To describe the modifications to the Haldane method used by the U. S. Navy and present the basis for these changes.

(3) To update the method presented by Dwyer by demonstrating the general case for decompression calculation rather than for air alone.

(4) To provide some textual material for use by student submarine medical officers.

1.2 Scope

1.2.1 This report considers several of the approaches to decompression calculations alternate to the "Haldane method" which have received attention in recent years.

1.2.2 The theoretical justification to the present form of the "Haldane method" as modified for use in the U. S. Navy is presented together with the control limits used for calculation of nitrogen-oxygen and helium-oxygen dives.

1.2.3 An attempt has been made to demonstrate the calculation procedure in step-wide fashion to implement the theory of exponential gas exchange.

2. DESCRIPTION

2.1 Development of the Haldane method

2.1.1 The first systematic study of decompression requirements following exposure of animals and man to increased ambient pressure of air was reported by Boycott, Damant and Haldane in 1908. As a result of numerous pressure exposures of small animals and goats, a rational basis for calculation of decompression schedules was derived. The basic tenets of their procedure, which has become known as the "Haldane method", relate to (1) the estimation of the percent of complete saturation or desaturation of the body tissues with nitrogen during any pressure exposure time-course, and (2) the amount of excess nitrogen pressure in the tissues related to hydrostatic pressure which is permissible without symptoms of decompression sickness resulting during or following the reduction of pressure to one atmosphere.

2.1.2 The processes of saturation and desaturation were considered in the following manner. The blood passing through the lungs of a man breathing compressed air becomes instantly saturated to the full extent with nitrogen at the existing partial pressure in the air. When this blood reaches the systemic capillaries, most of the excess nitrogen will diffuse out into the body tissues, and the blood return to the lungs for a fresh charge. This process is repeated until the tissues are equilibrated with nitrogen at the same partial pressure as in the air breathed. But the blood supply to different parts of the body varies greatly as does the capacity for dissolving nitrogen. It can be seen that the time taken for different parts of the body to become saturated with nitrogen will vary greatly.

2.1.3 Boycott, Damant and Haldane estimated that the whole body of a man weighing 70 kg. will take up about 1 liter of nitrogen for each atmosphere of excess air pressure, about 70% more nitrogen than an equal amount of blood would take up. With the weight of blood in man equal to 6.5% of the body weight, the amount of nitrogen held in solution in the completely saturated tissues would be about 170/6.5, or 26 times as great as the amount held in the blood alone. If the composition of the body were the same in all parts, and the blood distributed itself evenly to all tissues, the body would receive at one complete round of the blood after sudden exposure to increased pressure of air one twenty-sixth of the nitrogen corresponding to complete saturation. Each successive round would add one twenty-sixth of the remaining excess of nitrogen. Thus, it is seen that the body would be half-saturated in less than twenty rounds of circulation, or about ten minutes, and that complete saturation would be practically complete in an hour. The progress of saturation would follow an exponential curve, but it was considered a mistake that this rate of saturation and desaturation could be applied to the body as a whole. Actually the rate of saturation would vary widely in different parts of the body, but for any particular part the rate of saturation would follow a curve of this form, assuming that the circulation rate remained constant.

2.1.4 A variable rate of saturation and desaturation was considered to exist for different parts of the body, relating to the different perfusion rates of tissues with blood. This variable time-course of nitrogen uptake for various parts of the body was simulated by use of a family of discrete hypothetical half-time tissues (5, 10, 20, 40 and 75 minutes) to represent the physiologic processes of gas exchange in the whole body.

2.1.5 In their work with goats, the differences in respiratory exchange rate and cardiac output from man were considered. These were related to man as being two-thirds greater for the goat per kilo of body weight by direct measurement. Thus, a time of 3 hours was thought to be required for complete saturation for goats, while 5 hours was considered required for man. The 75 minutes of half-time would represent 7.5 hours time to 98.5 percent saturation. Therefore, it appears that an attempt was made toward conservatism or in considering that more time might be required for equilibration with nitrogen in some subjects.

Toward defining this, time of exposure to increased pressure was varied in animal experiments, the exposure pressure and decompression time remaining constant. It is not evident from the data reported that equilibration time was defined for man, as most exposures were not sufficiently long. This defect became apparent in the inadequacy of schedules for longer dives derived by this method until half-times of 120 to 240 minutes were used.

2.1.6 Perhaps more important than the estimation of uptake and elimination of nitrogen is the concept of stage decompression which developed from their studies. This makes the fullest use of the permissible difference in pressure between that of the tissue and blood nitrogen to hasten the elimination of nitrogen from the tissues. The limit applied to reduction of hydrostatic pressure was to never allow the computed nitrogen pressure in the tissues to be more than twice the ambient pressure. This 2 to 1 ratio actually assumed equilibration to the ambient pressure of the maximum depth, rather than to the nitrogen partial pressure. The absolute pressure of the maximum depth was then halved to determine the first decompression stop. A special case was assumed for air, for with its 79 percent nitrogen content, the actual ratio of nitrogen pressure upon equilibration to ambient pressure would be

$$\frac{2 \times 0.79}{1} = \frac{1.58}{1} \text{ in place of } \frac{2}{1}$$

2.1.7 It is true that this ignores the presence of oxygen in the breathing mixture as a factor in bubble formation. Extensive diving with nitrogen and helium mixtures enriched with oxygen in excess of 21 percent confirms the absence of significant effect of oxygen as part of the total pressure in decompression. It appears that if sufficient time is permitted for excess oxygen in tissues to be utilized during reduction of pressure, decompression sickness due to this factor is unlikely to occur.

2.1.8 The importance of the initial ascent to initiate the maximum safe gradient for inert gas elimination cannot be overemphasized. Prior to recognition of this concept, ascent to the surface was carried out at a constant rate which unnecessarily exposed the diver to pressure, resulting in further inert gas uptake in tissues which had not completely equilibrated. This increased the magnitude of decompression time required over that actually needed if the diver had achieved the initial decrease in depth compatible with safety. Only the special case of complete total body equilibration requires a continuous ascent at a constant rate to permit the use of a maximum safe gradient for inert gas elimination from the slowest half-time tissue controlling. Even this can follow an initial more rapid reduction of pressure of the order of one atmosphere.

2.1.9 Studies of permissible decrease in pressure considered the two cases of (1) reduction by some absolute value and (2) of that relative to ambient pressure. Haldane noted that goats decompressed from exposure at 6 atmospheres absolute to 2.6 atm had no symptoms. This is a 2.3 to 1 ratio of ambient pressure, with an absolute pressure change of 3.4 atmospheres. Goats were then similarly exposed at 4.4 atmospheres absolute pressure before being decompressed to 1 atmosphere. With the same 3.4 atmospheres absolute pressure change only 20 percent of the animals escaped symptoms.

2.1.10 Decompression schedules for man based on the 2 to 1 ratio concept have not proven to be safe for longer and deeper exposures. Haldane himself recognized this in his book "Respiration" by stating that for air dives exceeding 6 atmospheres absolute, some reduction of this ratio was required.

2.2 Further studies to define decompression limits

2.2.1 Studies by Hawkins, Shilling and Hansen and others by VanDerAue demonstrated that:

(1) the faster half-time tissues sometimes control deep stops even with high tissue ratios.

(2) tissue ratios must be reduced considerably for all components in longer and deeper dives.

(3) the surfacing ratios could be increased to the following values:

half-time (min)	tissue ratio	M(ft.)	M_{actual} (ft.)
5	3.8:1	125	99
10	3.4:1	112	88
20	2.8:1	92	73
40	2.27:1	75	59
75	2.06:1	68	54
120	2.00:1	66	52

The above values were used with slight modification to develop the present Standard Air Decompression Tables.

2.2.2 Ratios used at depth were projected from the surfacing values by using a tenth-power relationship between the tissue ratio at surface and at depth of decompression stop to fit existing data.

$$M = 33 \left[\left(\frac{rs}{rd} \right)^{10} + rd - 1 \right]$$

M = maximum final tissue pressure in feet of sea water

rs = surfacing ratio

rd = depth ratio at stop

2.2.3 Values for M in which only nitrogen is considered are derived by multiplying by 79 percent those developed with air considered as 100 percent nitrogen, or the absolute pressure of the exposure. With the values for slower half-time tissues required for longer and deeper exposures, the allowable surfacing values are:

half time (h)	5	10	20	40	80	120	160	240
M (ft)	104	88	72	56	54	52	51	50
$\Delta M/\Delta 10$ ft.	+18	+16	+15	+14	+13	+12	+11	+11

2.2.4 A linear projection of the M values to decompression stops at depth is described by a constant additive value listed as $\Delta M/\Delta 10$ ft. This projection is somewhat more conservative than values resulting from the tenth-power relationship described above. Deeper stops are required by this method, though reduction of gradient for elimination of nitrogen is not excessive. Dives calculated with these M values have been safe through a wide range of depth and time of exposure. The linear projection of M values is useful for computer programing as well.

?.2.5 The question as to why the faster half-time tissues permit greater nert gas tensions upon surfacing and at progressively deeper depths than he slower tissues must be faced. Graphical solution of the time-course f inert gas tension permitted for the various half-time tissues upon surfacing shows that within 16 minutes all inert gas tensions of half-ime tissues are less than, or equal to, the value for the 120 minutes alf-time tissue. Thus, the excess saturation time-course is brief for ll except the slower half-time tissues. The same statement can be made or the inert gas tensions permitted at the various decompression stops. s there should be a time-concentration course of probability for bubble ormation, a brief time-course of greater excess saturation may be as safe s a sustained time-course of lesser excess saturation. It is apparent rom this hypothesis that the magnitude of permissible excess saturation ime-course may vary appreciably between that which is sustained during ontinuous ascent and that which is periodic with stage decompression.

2.2.6 An important factor of difference in permissible tissue tension values for various half-time tissues may well be the greater molar concentration of inert gas for some slow tissues resulting from greater solubility of inert gas in these tissues. As molar concentration of inert gas increases in a tissue the probability or bubble formation would increase upon reduction of hydrostatic pressure as a greater number of gas molecules are available in excess of that held in solution at saturation. In some measure the permissible final tissue pressure values for the various half-time tissues will reflect this variable molar concentration as a time-concentration course permissible to avoid bubble formation in tissues of varying solubility for inert gas.

2.3 Further experiments in gas uptake and elimination

2.3.1 Subsequent experiments in uptake and elimination of nitrogen and other inert gases by Behnke and Shaw have yielded quantitative data to validate the gas exchange processes indicated by Boycott, Damant and Haldane. From data obtained in a series of studies on dogs and human subjects they concluded:

(1) that nitrogen absorption is proportional to the partial pressure of nitrogen in the lungs.

(2) that with the same pressure head, the rate of nitrogen absorption is equal to the rate of nitrogen elimination.

(3) that the time for complete nitrogen elimination, and percentage rate of nitrogen elimination for corresponding periods of time, are the same irrespective of the quantity of nitrogen absorbed by the body.

2.3.2 However, the precise end-point of nitrogen elimination could not be measured with accuracy, with the result that the slowest tissues to be considered in calculation of decompression schedules appeared to be those that were 98 ± 2% desaturated at the end of 6 hours. This led to the conclusion that it was unlikely that compressed air illness following long exposure to increased pressure resulted from an underestimation of the time required for nitrogen elimination. Experimental values for the nitrogen elimination curve gave further support to the multiple tissue theory of calculation developed by Haldane by demonstrating the variation in distribution of blood flow in relation to the distribution of nitrogen in the body.

2.4 Factors of difference in exchange of various inert gases

2.4.1 When trying to analyze the mechanism of gas uptake and elimination, there are at least two factors, assuming respiration and cardiac output to remain constant, which govern the saturation or desaturation half-time for non-reactive gases:

(1) capacity of the tissue for storage of gas

(2) effectiveness of gas transport to and from the tissues.

It is obvious that if a tissue is continuously perfused by blood, supposing the gas to be carried away at a certain rate, the time required for elimination is longer the greater the gas content of the tissue. If different gases are compared for the same tissue, the storage capacity is proportional to the solubility coefficients for the gases in the tissue. At the same time, the period for gas equilibration between tissue and blood is shorter the better the gas transport.

2.4.2 From the body gas exchange curve

$$Pt = Po\ e^{-kt}$$

Where Pt = tension of gas after time t

Po = tension of gas at t = o

e = base of natural logarithm

k = constant of elimination

the value of k is found to not remain constant, but to decrease progressively, the shape of the curve thus differing from those of its hypothetical and exponential components each having its own constant k.

2.4.3 By definition, the half-time (h) is that time required to reduce Po to half its original value. For each discrete value of k, therefore

$$h = \frac{0.693}{k}$$

$$k = c \times \frac{C}{S}$$

Where: c = a constant of proportionality

C = symbol of gas transport effectiveness

S = solubility coefficient for the gas in a tissue

Therefore, the desaturation half-time (h) is also proportional to the solubility coefficient of the gas in a particular tissue, and inversely proportional to the effectiveness of gas transport from the tissue.

$$h = \frac{1}{c} \times \frac{S}{C}$$

2.4.4 In highly vascularized tissues, the high blood-tissue perfusion rate may mask differences in diffusion rates of inert gases, half-time for different gases in the tissue varying only as determined by the solubility coefficients. For poorly vascularized tissues, equilibration half-times of different gases should vary as determined by solubility coefficients plus diffusion rates.

2.4.5 Theoretically, the body-exchange curve representing the rate of uptake and elimination of inert gas by the body as a whole is the sum of an infinite number of exponential curves with different half-times, each representing tissue regions with the same individual ratio of fat-fluid content to efficiency of gas transport. Helium having a low solubility in fat compared to nitrogen may yield a shorter half-time than nitrogen in a tissue rich in fat and having an efficient gas transport. The differentiation of an amount of tissue defined by a nitrogen half-time into several types of tissue having different half-times when another gas is substituted for nitrogen is in accordance with the results of Jones et. al., which support the principle that the varying decay terms of the component exponential expression (e^{-kt}) are not to be referred to as anatomically defined phases.

2.4.6 In fatty tissues the exchange rates differ from the blood-tissue perfusion rate by a factor of the ratio blood solubility/tissue solubility of the gas concerned. Thus, for helium, the final concentration in the fatty tissues will be less than for nitrogen when the exposure is to the same partial pressure of these gases due to the lower fat solubility of helium ($He/N_2 = 1/4.5$). However, some of the slow tissues may be characterized more by a poor blood-tissue perfusion rate than by high fat content, differences in fat solubility of the gases having less influence on the elimination time. Thus, the different kinds of arbitrary tissues within the same half-time class may well represent different fat-fluid ratios and blood-tissue perfusion rates, though the average of their ratios is constant. If helium is substituted for nitrogen, the classification, which is a physiological rather than an anatomical one, may cause new tissue combinations to arise with common half-time for this gas. Theoretically, the arrangement of different half-time groups will remain unchanged from one gas to another only for gases with the same fat-water solubility ratio, as for argon and nitrogen at 5.2/1. Thus, the half-time would be multiplied by the ratio of argon/nitrogen solubility coefficients in oil and water (2/1).

2.4.7 It has been determined experimentally that for helium diving somewhat deeper decompression stops are required to prevent bends than for air diving. Behnke considered this to be due to the rate of helium diffusion into the blood stream being more rapid than for nitrogen, thus making bubble formation more likely if the early stages of decompression are too rapid. However, comparison of the helium and nitrogen elimination curves for subjects demonstrates the quantity of helium eliminated to be one-third that of nitrogen for any comparable time period. Recent studies of bubble growth and resolution in water have indicated that the growth rate of helium bubbles in solutions of equal concentrations of the respective gases should be six times greater than for nitrogen bubbles. This is due to the lesser solubility and greater diffusibility of helium in either aqueous or fatty tissues.

2.5 Decompression studies based on the whole body gas exchange process

2.5.1 Several attempts have been made to develop decompression calculation procedures based upon the whole body uptake and elimination curves for nitrogen and helium. Behnke devised a method in which the quantity of excess nitrogen taken up during any depth-time exposure was related to the percent of whole body uptake of nitrogen with time on the whole body gas exchange curve. Decompression schedules prepared on the basis of this method were not reported.

2.5.2 Several workers at the Royal Naval Physiological Laboratory have been the most recent proponents of this method. Hempleman found a good correlation of the minimal decompression dives permissible when air is breathed, to a constant value as follows:

$$k = D\sqrt{T}$$

where: $k = 500$

D = depth in feet of sea water

T = exposure time in minutes

2.5.3 It was noted that this method did not accurately predict the depth of the permissible exposure in excess of 100 minutes. The form of the equation appeared to be similar to that for diffusion processes, so that further definition of this method has been in developing equations to simulate the diffusion gas exchange process.

2.5.4 Rashbass further expanded the development of the theory of the diffusion-limited gas exchange process using modifications of equations developed by A. V. Hill to explain diffusion of oxygen in various geometrical models of tissues. A limit of 30 feet of excess gas taken up was permitted at any ambient pressure. Dive schedules calculated by this method required deeper stops than conventional air schedules, and time spent at shallower stops tended to be of equal length. While shorter working dives in the dry chamber were reasonably safe, open-sea testing of these schedules produced a high incidence of bends.

2.5.5 Duffner applied a similar calculation procedure to that of Hempleman in deriving decompression schedules for helium-oxygen dives with mixed gas scuba. He developed the following power function equation to fit experimentally determined minimal decompression dives:

$$Q = DAt^x$$

Q = excess helium in feet of sea water = 37 ft.

D = exposure depth in feet of sea water

A = constant equal to the fraction of available excess helium in feet of sea water taken up when t = 1

t^x = time in minutes

x = 1

Values of At^x from 1 to 180 minutes were derived and presented in tabular form. The time to be spent at a decompression stop is determined by the following equation:

$$t = \left[\frac{Q - (37 + DNS)}{(Q - Ds)0.083}\right]$$

Ds = depth of present stop

DNS = depth of next stop

2.5.6 Decompression schedules calculated by this method either for air or helium-oxygen dives relate closely to those derived by the Rashbass method; that is, deeper stops are required, and the shallower stops for longer exposures tend to be of the same duration. A comparable result can be obtained by use of a single half-time tissue of 60 minutes with a 2 to 1 ratio limiting, when the Haldane method is employed. Thus, it is apparent that insufficient consideration of slower half-time tissues representing poorly perfused areas of the body is given by the diffusion-limited methods of calculation as presently constituted. Longer and deeper dive schedules calculated by these methods have proven to be grossly inadequate in providing safe decompression.

2.6 Definitions and symbols

2.6.1 Depth (D) is the vertical distance below the surface at any phase of the dive. The units of depth are feet of water.

2.6.2 Absolute depth (A) is the absolute pressure at any depth (D) expressed in feet of water. A is always 33 feet greater than D, except in the special condition of diving at other than sea level, as in a mountain lake.

2.6.3 The oxygen percentage decimal (X) expresses the oxygen content of the breathing medium during each phase of the dive.

2.6.4 The inert gas percentage decimal (G) expresses the inert gas content of the breathing medium during any phase of the dive. It is derived by substracting the breathing medium oxygen percentage decimal (X) from unity (1.00).

2.6.5 The inert gas partial pressure (N) represents the sum of the partial pressures of all gases in the breathing medium other than oxygen. N is derived by multiplying the absolute depth (A) by the inert gas percentage decimal (G). Special procedures may require handling several inert gases separately, as in the calculation of helium-oxygen decompression schedules.

2.6.6 The initial tissue pressure (P) is the partial pressure of inert gas in a tissue at the start of any particular time interval. When there has been no dive within 12 hours prior to the dive being considered, the initial tissue pressure for all tissues at the start of the dive is taken as that in air. For repetitive dives within a 12 hour period, the amount of inert gas remaining in tissues must be calculated during the time interval on the surface. For each step in the decompression calculation, the final tissue pressure (Q) of one step becomes the initial tissue pressure (P) of the next step.

2.6.7 The differential pressure (E) is the difference between the inert gas partial pressure (N) of the breathing medium and the initial tissue pressure (P). (E) represents the driving force for inert gas exchange, being positive (+) if (N) is greater than (P), indicating that the tissue gains inert gas. The value of E is negative (-) if (N) is less than (P), indicating that the tissue loses inert gas.

2.6.8 The tissue pressure change (S) is the increase or decrease of tissue pressure during a time interval, resulting from the existence of a differential pressure (E). It is derived by multiplying (E) by the time function (F) for the time interval. (S) is positive (+) or negative (-) according to the sign of (E).

2.6.9 The final tissue pressure (Q) is the partial pressure of inert gas in the tissue at the end of a time interval. (Q) is the sum of (P) and (S). (Q) for one interval becomes (P) for the next interval.

2.6.10 The time interval (T) is the duration in minutes of any specific phase of the dive considered. These phases are usually taken as (1) the exposure (2) the ascent (3) the first stop (4) each of the subsequent stops (5) in repetitive dives, the surface interval.

2.6.11 The exposure time interval includes both time of descent and time at depth. Unless descent is slower than the normal rate, there is no separate calculation for descent time.

2.6.12 The ascent time interval depends on the depth of the first stop and the rate of ascent. In standard diving practice the rate is 60 feet per minute or less.

2.6.13 The time interval (T) at each stop depends on the length of time required to desaturate the "controlling tissue" to a (Q) equal to or less than the maximum tissue pressure (M) permitted for the next stop.

2.6.14 The surface time interval must be considered when it is less than 12 hours to the next dive. The (Q) at the end of the surface interval is the (P) for the next exposure.

2.6.15 Saturation is the process of gaining inert gas during exposure to a positive differential pressure (E). The process is complete when (Q) equals (N) in the breathing medium.

2.6.16 Desaturation is the process of losing inert gas during exposure to a negative differential pressure (E). This is complete when (Q) equals (N) in air at the surface.

2.6.17 The tissue half-time (H) is the specific time interval (T) required to produce a tissue pressure change (S) equal to half of the differential pressure (E) acting at the beginning of the interval. In calculations, tissues are designated by their half-time. The body is probably composed of an infinite number of tissues with half-time from zero to 240 minutes or more. For calculations the range of tissues is sampled in a geometrical progression of half-times consisting of 5, 10, 20, 40, 80, 120, 160, 200 and 240 minutes. A 40 minute increment of half-time tissues is used in excess of 40 minutes half-time to insure adequate sampling of time obligation for decompression.

2.6.18 The time unit (U) is the number of half-times in a given time interval (T) for a tissue with a specific half-time (H). It is therefore the ratio (T/H) of the time interval to the half-time of the tissue, and is dimensionless. The time unit (U) is different for each tissue half-time (H) being considered for a given time interval (T). The time unit normally ranges from 0.000 to 6.000, and is related to the time function (F) as follows:

$$F = 1 - 1/2^{u}$$

Tables of time unit against time function, and time function against time intervals for specific half-times are used in calculations.

2.6.19 The time function (F) is the ratio of the amount of change (S) to the differential pressure (E). When a differential pressure(E) acts on a given half-time tissue, the initial tissue pressure (P) changes by a specific amount (S) in any given time interval (T). The total amount of change (S) increases with the time interval (T), so that the time function (F) also increases. The value varies from 0.000 to 1.000 in a special relation to the time unit.

2.6.20 Since $F = S/E$, then $S = FE$. Thus, the amount of change in tissue pressure for a specific time interval can be determined. During decompression a certain amount of tissue pressure change (S) must occur during the time interval (T) to reduce the final tissue pressure (Q) to within limiting values of (M), so that depth can be decreased by ten feet to the next stop. The time interval required is determined from the relationship $F = S/E$.

2.6.21 The maximum tissue pressure (M) is the greatest partial pressure of inert gas in a specific tissue which will not permit bubbles to form in the tissue at a given absolute pressure. The values of (M) for each half-time tissue and depth of decompression stop are tabulated for convenience in calculation. The final tissue pressure (Q) must fall to or below the values of (M) for the next stop before ascent to that stop.

2.6.22 Values of (M) are derived from safe minimal decompression exposures of variable depth and time to the inert gas mixture being considered, as air or helium-oxygen. From these exposures, the value of (Q) upon surfacing is calculated for each half-time tissue to derive the maximum permissible values of $Q = M$. As discussed previously, the values of (M) could not be safely projected for decompression stops on the basis of a constant ratio to ambient pressure as indicated by Haldane. Following a considerable amount of evaluation of experimental dives, a method of projecting (M) values to depth of stops with a constant factor of increase per 10 feet depth change has been developed. This relates closely to the tenth-power relationship of surface to depth ratio of Dwyer, but permits greater flexibility. The rate of change of values of (M) with absolute depth varies with the inert gas breathed, as also do the permissible surfacing values. Thus, values of (M) for air dives do not provide sufficient depth of decompression stops for helium dives (Tables N and H).

2.6.23 Supersaturation is an unstable state occurring when the initial tissue tension (P) exceeds a value of the inert gas partial pressure (N), which represents the maximum equilibration state of the gas in a tissue at the absolute pressure. The maximum tissue pressure (M) allowable at any given absolute depth is a value exceeding (N) such that the tissue will not release inert gas in the form of bubbles. The initial tissue pressure (P) is always greater than (N), such that the differential pressure (E) is algebraically negative, and the tissue will lose inert gas.

2.6.24 The controlling tissue for ascent is that which must stop at the greatest depth to avoid bubble formation, and for a given stop is that which requires the longest time to desaturate to the maximum tissue pressure (M) permitted at the next stop. At a given decompression stop some initial tissue pressures (P) will be greater than the corresponding maximum tissue pressures (M) permitted at the next stop. Each final tissue pressure (Q) must be equal to or less than the maximum tissue pressure (M) for the next stop before the tissue can ascend to that stop.

2.7 Theory of exponential saturation

2.7.1 The need for decompression arises when tissue saturation with inert gas reaches the point that the tissue can no longer surface directly without bubble formation. This is necessary for saturation dives on air exceeding 33 feet, and 37 feet when 80 - 20% HeO_2 is breathed.

2.7.2 Final tissue pressure (Q) at the end of any time interval (T) is the sum of the initial tissue pressure (P) and the tissue pressure change (S) during the interval.

$$Q = P + S$$

2.7.3 Initial tissue pressure (P) at the start of an interval is the final tissue pressure (Q) for the preceding interval.

$$P_2 = Q_1$$

2.7.4 Tissue pressure change (S) during an interval depends on the existence of a differential pressure (E) and the exponential function (F) of the time interval (T). The tissue pressure change (S) is the product of the time function (F) and the differential pressure (E).

$$S = (F)(E)$$

2.7.5 The differential pressure (E) is the difference between the inert gas partial pressure (N) to which the tissue is exposed and the initial tissue pressure (P) at the start of the exposure.

$$E = N - P$$

2.7.6 The time function (F) is a specific exponential function of the time unit (U).

$$F = 1 - 1/2^U$$

2.7.7 The time unit (U) is the ratio of the time interval (T) to the half time (H).

$$U = T/H$$

2.7.8 The entire theory of exponential tissue saturation can be expressed in a single equation as follows:

$$\begin{aligned} Q &= P + S \\ &= P + (F)(E) \\ &= P + (1 - 1/2^{U})E \\ &= P + (1 - 1/2^{U})\ (N - P) \\ &= P + (1 - 1/2^{\frac{T}{H}})\ (N - P) \end{aligned}$$

2.8 <u>Theory of control of excess saturation of tissues</u>

2.8.1 A tissue can hold some amount of dissolved inert gas in supersaturation. The amount depends on the absolute pressure around the tissue. Haldane considered the ratio of maximum tissue pressure (M) to absolute depth (A) to be a constant for all half-time tissues. Prior discussion has considered the application of a relative relationship of (M) >(A) dependent on (A) and the specific half-time tissue (H).

2.8.2 A tissue gains inert gas during a dive. At the end of the dive, the absolute depth to which the tissue can ascend is determined by the tissue pressure at the end of ascent. Values of maximum allowable tissue pressure (M) at 10 foot increments of stops are presented in tabular form for both nitrogen-oxygen and helium-oxygen dives. (Tables N and H).

2.8.3 At each decompression stop the controlling tissue determines the time interval (T) for the stop. The final tissue pressure (Q) must be equal to or less than the value of (M) for that tissue permitted at the next stop before all tissues may ascend to that stop.

$$Q \leq M$$

2.8.4 The minimum tissue pressure change (S_{min}) required at a stop is at least the difference between the initial tissue pressure (P) and the value of (M) at the next stop.

$$S_{min} = M - P$$

2.8.5 The differential pressure (E) for the controlling tissue is:

$$E = N - P$$

Both (S) and (E) are algebraically negative. The ratio (S/E) of the required tissue pressure change to the acting differential pressure is the least value of the time function for the controlling tissue at a given stop.

$$F\ min = S\ min/E$$

The least time function (F min) corresponds to some minimum time unit (U min) and to some minimum time interval (T min) for the controlling tissue half-time (H).

2.8.6 Control generally shifts from the faster to slower half-time tissues during decompression. During the deeper stops the slow tissues frequently have positive values of (E) and continue to gain gas at these stops. Subsequent requirement to lose gas places these slower tissues in control at the shallower stops.

2.8.7 Table U is a tabulation of time function (F) against time unit (U). Values of (F) are given to three decimal places, and (U) to two decimal places. The left-hand column shows the integer and the first decimal of the time unit. The other columns are headed by the second decimal of the time unit, and show the corresponding time function.

2.8.8 Table T is a tabulation of time interval (T) in minutes from 1 to 150 and time function (F) for the various half-time tissues.

2.9 Decompression calculation worksheet

2.9.1 Minimal calculation of decompression requires handling the several tissues simultaneously. This is aided by use of the worksheet on which the entire dive is divided into several steps (Figure 1).

(1) Exposure

(2) Trial first stop and ascent

(3) First stop

(4) Succeeding stops

(5) Surface interval

2.9.2 The top section is for ambient conditions for any phase of the dive, including D, A, N and T. The other sections are divided into U, F, E, P, S, Q, and M. A special section box (G) is provided, though this may vary with the breathing mixture during the dive. Box (H) provides for six different half-times to be considered (Figure 1).

3. PROCEDURE

3.1 Calculation of decompression schedules

3.1.1 The various components of the calculation required to derive the final tissue tension (Q) for each step of the dive have been defined in prior discussion.

3.1.2 Where

$$Q = P + S$$
$$P = N = G \times A$$

when there has been no previous pressure exposure for 24 hours. The inert gas partial pressure of the breathing medium (N) at each phase of the dive is derived similarly:

$$N = G \times A$$

3.1.3 The time function (F) is then determined for the exposure period time interval (T) from Table T, or Table U, if this exceeds 150 minutes.

3.1.4 E can then be determined from N - P, as these values are known.

3.1.5 S is then determined from FE, the algebraic sign being observed.

3.1.6 Q then equals P + S, added algebraically for each half-time tissue at each step of the dive.

3.1.7 Depth of first stop is determined for (Q) resulting from the time interval (T) accrued at 60 fpm ascent.

3.1.8 The value of (N) is determined as the mean value between that of the exposure depth and that of the first stop.

3.1.9 A trial first stop is evaluated by comparing values of (P) at beginning of ascent to values of (M) for the various half-time tissues.

3.1.10 The resulting (Q) values after ascent, as affected by change (S) = FE, must be equal to or less than the value of (M) for each half-time tissue, (Table N and H)

3.1.11 The time interval (T) required at each stop is determined from the expression F = S/E where S = P - M, the change in (P) required to reduce it to a value equal to or less than M permitted at the next stop ten feet shallower for all half-time tissues (H).

3.1.12 The time interval (T) is thus calculated for each subsequent decompression stop until the surfacing value of (M) is reached and ascent to the surface permitted.

3.1.13 Calculation of the surface time interval (T) is necessary in the analysis of repetitive dives, to determine the initial tissue pressure (P) at the start of succeeding dives. The procedure is identical to that described. with the initial tissue pressure (P) being the final tissue pressure (Q) upon surfacing from the preceding dive.

3.2 <u>Calculation worksheet</u>

3.2.1 A sample calculation worksheet is included as Figure 2 to demonstrate a sample calculation for a 180 foot-30 minute air dive. Values of M for nitrogen-oxygen dives from Table 1 are used.

3.2.2 Figure 3 demonstrates the calculation procedures used for a 200 foot 30 minute helium-oxygen dive in which 75 - 25% HeO_2 is breathed during the exposure and ascent to a depth of 50 feet, where oxygen decompression is begun until surfacing is permitted. Table 2 gives values of M for helium-oxygen dives.

3.3 <u>Calculation of oxygen decompression</u>

3.3.1 Oxygen decompression is usually considered to be 80% efficient due to leakage of air or helium into the mask. Thus, in deriving N = GA, G = 0.2 as the inert gas fraction. When oxygen is breathed at one or more atmospheres pressure for in excess of 30 minutes, some reduction in tissue perfusion occurs to effectively prolong the time required to eliminate inert gas from the tissue. Reduction of tissue perfusion by 25 percent will require 133 percent of the time to accomplish the same perfusion for each half-time tissue. This factor may be applied to the time interval (T) derived by the regular calculation procedure when oxygen breathing is sustained for 30 minutes or more.

3.4 <u>Calculation of decompression for deeper working dives</u>

3.4.1 It is also recognized that inert gas uptake during work will be greater than during rest due to increased cardiac output and tissue perfusion. Elimination of inert gas during rest periods will also be more prolonged than during work. Determination of M values for working dives does provide for the difference in inert gas uptake in some measure.

3.4.2 However, as the depth of the dive increases, the differential pressure (E) becomes greater than for minimal decompression dives for which surfacing M values are derived. It appears that for dives in excess of 200 feet, some factor must be multiplied by the time interval of the exposure to provide for the additional inert gas uptake with work. A factor of 1.5 provides well for many dives tested, though a factor of 2.0 was used in calculation of the helium-oxygen schedules in the present diving manual.

4. RESULTS

4.1 Decompression Schedules

4.1.1 Upon completion of the calculations for the ten foot stop, tabulate the data for the decompression schedules as follows:

Depth (ft)	Bottom time (min)	Time to first stop (min)	Decompression stop (min) (ft) 40	30	20	10	Total Ascent time (min)
200	30	2.7	2	9	22	37	73

Breathing mixture: air (79 - 21% Nitrogen-oxygen)

(1) For the dive exposure show the depth and time

(2) For the ascent show the time to the nearest tenth of a minute

(3) For the decompression stops show the depth in feet and time in minutes

(4) Show the total ascent time in minutes

(5) Show the breathing mixture percentage of inert gas and oxygen. If this changes during the exposure period or at decompression stops, this must be noted at these depth and times.

5. DISCUSSION

5.1 Other methods

5.1.1 Several other methods can be used to calculate decompression schedules. No attempt has been made to present all the possible methods or to assess these critically. All those based on Haldane's theories give similar results, varying only with the controlling limits of excess saturation permitted at various ambient pressures, when the same breathing mixtures are employed.

5.1.2 The necessity to consider longer half-time tissues for deeper and longer exposures has only recently become apparent. This has been necessary for helium-oxygen dives, as well as those in which nitrogen-oxygen mixtures are breathed. For the most part, dive exposures have not been of sufficient magnitude to test this requirement until recently. This is only a necessary modification to the basic method devised by Haldane.

5.1.3 Testing of dive schedules developed by the methods employing a diffusion-limited inert gas exchange formulation have been the only others considered adequate to permit a judgment. For the most part the results have not been as satisfactory as the schedules developed by the Haldane method, as modified for use by the U. S. Navy. It is possible that further effort with the former method may be more rewarding.

5.1.4 Continuous ascent decompression can be calculated by the method presented, as well as stage decompression. The mean absolute depth (A) and inert gas partial pressure (N) of the breathing medium is calculated for the increment of depth change considered. The time required for the controlling tissue to lose a sufficient amount of inert gas to ascend to the depth desired is then calculated. The procedure is followed until the surface is reached.

5.1.5 Control of continuous ascent is possible in the decompression chamber after transfer of the diver under pressure from the submersible decompression chamber. It is not possible in the water unless conditions are optimal for accurate depth keeping, which is seldom the situation in open sea diving.

5.1.6 There are several theoretical advantages of continuous ascent decompression over the stage method. First, the maximum safe gradient (E) for elimination of inert gas can be maintained to result in reduction of decompression time required for the same dive exposure. The greatest time saving occurs in decompression from saturation dives, where the slowest half-time tissue controls. Maintenance of the maximum safe gradient will permit elimination of the excess inert gas in about one-fourth the time required by the stage method under such conditions.

5.2 Inadequacies of decompression prediction

5.2.1 The present information concerning concentration of various inert gases at anatomical sites during the elimination time-course is quite inadequate. Whole body inert gas elimination studies of exhaled gas are not particularly helpful in further defining this information. Increasing refinements of this technique are also unlikely to produce information that is particularly helpful. Data needed can only be derived from inert gases which are tagged with radioactive tracers. Unfortunately, the gases of interest, nitrogen and helium, do not have isotopes of sufficient half-life to make this a useful method. Since the gases with longer isotope half-life as xenon and kryton have much greater solubility coefficients in tissues than nitrogen and helium, their tissue concentrations are not apt to be predictive of those of the respirable gases of interest. Thus, much dependence is still placed on design of decompression studies to attempt to define permissible inert gas time-concentration course in tissues during dive exposures.

5.2.2 Since quantitation of decompression adequacy is still dependent primarily on presence or absence of symptoms related to decompression sickness, definition is only relatively gross. Ultrasonic methods of bubble detection in vivo and in vitro are being explored to permit better definition of decompression adequacy, but this is still in its early stages. Observation of micro-circulation of the bulbar conjunctiva to detect changes in circulation, presence of intra-vascular agglutination, and possible presence of bubbles presents another possibility for quantitation, but this too is in an early stage of investigation.

5.2.3 Evaluation of decompression schedules is greatly complicated by marked intra and inter-individual differences in susceptibility to decompression sickness. Little is known of the mechanisms involved. A definite acclimatization occurs in caisson workers and divers through repeated exposure to pressure. Coincidental to these exposures may be a significant increase in physical conditioning with the work involved to improve cardiac output and tissue perfusion efficiency. An improvement of these factors should facilitate inert gas exchange efficiency, to thus reduce the excess saturation time-course of inert gas in tissues and decrease the probability for bubble formation. Excess fatigue and relative ill-health in divers has been observed to increase the risk of bends following schedules which have been safe on other occasions. Factors decreasing tissue perfusion such as exposure to cold or PO_2 of one atmosphere or more during the depth exposure and decompression, may also play an important part in prolonging the inert gas elimination such that prediction in the calculation procedure is grossly impaired. It is apparent that such variables impose severe constraints on any method of calculation to provide adequate decompression schedules.

5.3 Validity

5.3.1 The multiple tissue theory and the half-time exponential saturation theory have received criticism because the resultant decompression schedules are not always satisfactory. This is particular true of the schedules for long, deep dives. However, no other method has yet produced comparably satisfactory decompression schedules with such a low overall incidence of decompression sickness.

5.3.2 A recent review of air and helium dives in the U. S. Navy requiring decompression over a recent two year period gave an incidence of 0.69% and 0.83% bends, respectively. When it is considered that hundreds of no decompression dives were not included, and that not all the dive records were available, but that the reports of decompression sickness were available, this is a somewhat conservative estimate. Considering all the possible variables, it seems unlikely that very great improvement in the calculation procedure to provide safer schedules can be expected.

6. CONCLUSIONS

6.1 Conclusions

(1) This report provides background information on the development of the Haldane method of decompression calculation as modified for use by the U. S. Navy.

(2) Other methods of decompression calculation developed in recent years are reviewed and appraised in reference to that described above.

(3) The step by step procedure of calculation exployed is detailed as it implements the application of the theory. Examples of calculations of dive schedules are presented for both air and helium-oxygen dives.

6.2 Recommendations

(1) Computer programs have already been developed employing the basic format presented here. As the dive schedules calculated are tested, report the results of these evaluations with any modifications of the calculation procedure required to produce safe schedules.

(2) That this report be used for instruction to acquaint personnel with the theoretical basis of decompression calculations and to guide them in calculating dive schedules.

(3) That this report be revised or superceded as a text as this becomes necessary.

7. FIGURES AND APPENDICES

7.1 Figures

7.1.1 Figure 1 is a worksheet for the calculation of decompression schedules. The use of the worksheet and definition of symbols is described in the text.

7.1.2 Figure 2 is a sample decompression calculation of a 180 foot-30 minute dive on air using the worksheet in figure 1.

7.1.3 Figure 3 is a sample decompression calculation of a 200 foot-30 minute dive on 75-25% helium-oxygen using the worksheet in figure 1.

7.2 Appendices

7.2.1 Appendix A presents Table U, a tabulation of the time function against the time unit.

7.2.2 Appendix B presents Table I, a tabulation of the time function against the time interval for various tissue half-time.

7.2.3 Appendix C presents Table N, a compilation of maximum allowable tissue tensions (M) at decompression stops for nitrogen-oxygen dives.

7.2.4 Appendix D presents Table H, a compilation of maximum allowable tissue tensions (M) at decompression stops for helium-oxygen dives.

7.2.5 Appendix E presents Table D, a compilation of maximum allowable tissue tension (M) at decompression stops for air dives, based on a 10th power relationship of surface and depth ratios, used in calculation of the U. S. Navy Standard Air Decompression Tables.

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FIGURE 1 - WORKSHEET

	Air	Exp.	Asc.	1	2	3	4	
G .79	D	180		40	30	20	10	0
	A	213		73	63	53	43	33
	N	168	113	58	50	42	34	
	T	30	2.33	2	6	20	29	
H 5	U		.467					
	F	.985	.276	.242	.564	.937	.982	
	E	+142	-53	-94	-80	-43	-11	
	P	26	166	152	130	85	45	35
	S	+140	-14	-22	-45	-40	-10	
	Q	166	152	130	85	45	35	
	M		176	158	[illegible]	122	104	
H 10	U		.233					
	F	.875	.149	.129	.340	.750	.866	
	E	+142	-37	-87	-84	-64	-24	
	P	26	150	145	134	106	58	38
	S	+124	-5	-11	-28	-48	-20	
	Q	150	145	134	106	58	38	
	M		152	136	120	104	88	
H 20	U		.117					
	F	.646	.078	.066	.187	.500	.683	
	E	+142	-5	-60	-64	-60	-38	
	P	26	118	118	114	102	72	48
	S	+92	0	-4	-12	-30	-24	
	Q	118	118	114	102	72	48	
	M		132	117	102	87	72	
H 40	U		.058					
	F	.405	.040	.034	.098	.293	.395	
	E	+142	+29	-27	-34	-39	-36	
	P	26	84	85	84	81	70	56
	S	+58	+1	-1	-3	-11	-14	
	Q	84	85	84	81	70	56	
	M		112	98	84	70	56	
H 60	U		.029					
	F	.229	.020	.017	.050	.156	.222	
	E	+142	+54	-2	-10	-18	-23	
	P	26	59	60	60	60	57	52
	S	+33	+1	0	0	-3	-5	
	Q	59	60	60	60	57	52	
	M		106	93	80	67	54	
H 120	U		.019					
	F	.158	.013	.011	.034	.108	.154	
	E	+142	+64	+8	0	-8	-16	
	P	26	49	50	50	50	50	48
	S	+23	+1	0	0	0	-2	
	Q	49	50	50	0	50	48	
	M		100	88	76	64	52	

FIGURE 2 180' - 30 MINUTES AIR DIVE

Oxygen
G = 0.2

	HeO_2	Exp.	Asc.	1	2	3	4	5			
G / .75	D	200		60	50	40	30	20	0		
	A	233		93	83	73	63	53	33		
	N	175	123	70	17	15	13	11			
	T	30	2.33	2	2	3	5	19			
H / 5	U		.467								
	F	.985	.276	.242	.242	.340	.500	.927			
	E	+149	-40	-92	-123	-95	-65	-35			
	P	26	173	162	140	110	78	46	14		
	S	+147	-11	-22	-30	-32	-32	-32			
	Q	173	162	140	110	78	46	14			
	M		176	161	146	131	116	86			
H / 10	U		.233								
	F	.875	.149	.129	.129	.187	.293	.732			
	E	+149	-34	-82	-125	-111	-93	-68			
	P	26	157	[illegible]	142	126	106	79	29		
	S	+130	-5	-10	-16	-20	-27	-50			
	Q	157	152	142	126	106	79	29			
	M		158	144	130	116	102	74			
H / 20	U		.117								
	F	.646	.078	.066	.066	.098	.158	.482			
	E	+149	+1	-52	-102	-98	-91	-79			
	P	26	122	122	119	113	104	90	52		
	S	+96	0	-3	-6	-9	-14	-38			
	Q	122	122	119	113	104	90	52			
	M		144	131	118	105	92	66			
H / 40	U		.058								
	F	.405	.040	.034	.034	.050	.083	.280			
	E	+149	+36	-19	-72	-72	-71	-67			
	P	26	87	89	89	87	84	78	60		
	S	+61	+2	0	-2	-3	-6	-18			
	Q	87	89	89	87	84	78	60			
	M		132	120	108	96	84	60			
H / 80	U		.029								
	F	.229	.020	.017	.017	.026	.042	.152			
	E	+149	+63	+9	-44	-46	-47	-47			
	P	26	60	61	61	61	60	58	51		
	S	+24	+1	0	[illegible]	-1	-2	-7			
	Q	60	61	61	61	60	58	51			
	M		128	116	104	92	80	56			
H / 120	U		.019								
	F	.158	.013	.011	.011	.017	.028	.103			
	E	+149	+73	+19	-34	-36	-38	-39			
	P	26	50	51	51	51	51	50	46		
	S	+24	+1	0	[illegible]	0	-1	-4			
	Q	50	51	51	[illegible]	[illegible]	50	46			
	M		[illegible]	114	[illegible]	90	78	54			

FIGURE 3 200' - 30 MINUTES 75-25% HELIUM-OXYGEN DIVE

TIME UNIT (Integer and one decimal place)	TIME UNIT (Second decimal place) 0	1	2	3	4	5	6	7	8	9
0.0	——	.007	.014	[illegible]	.027	.034	.041	.047	.054	.061
0.1	.067	.073	.081	.086	.092	.099	[illegible]	.111	.117	.123
0.2	.129	.136	.141	[illegible]	.153	.159	.165	.171	.176	.182
0.3	.188	.193	.199	[illegible]	.210	.215	.221	.226	.232	.237
0.4	.242	.247	.253	.258	.263	.268	.273	.278	.283	.288
0.5	.293	.298	.303	.307	.312	.317	.322	.326	.331	.336
0.6	.340	.345	.349	.354	.358	.363	.367	.372	.376	.380
0.7	.384	.389	.393	.397	.401	.405	.410	.414	.418	.422
0.8	.426	.430	.434	.438	.441	.445	.449	.453	.457	.460
0.9	.464	.468	.472	[illegible]	.479	.482	.486	.490	.493	.496
1.0	.500	.503	.507	.510	.514	.517	.520	.524	.527	.530
1.1	.533	.537	.540	.543	.546	.549	.553	.556	.559	.562
1.2	.565	.568	.571	.574	.577	.580	.583	.585	.588	.591
1.3	.594	.597	.600	.602	.605	.608	.610	.613	.616	.618
1.4	.621	.624	.626	.629	.632	.634	.637	.639	.642	.644
1.5	.646	.649	.651	.654	.656	.659	.661	.663	.666	.668
1.6	.670	.672	.675	.677	.679	.681	.684	.686	.688	.690
1.7	.692	.694	.697	.699	.701	.703	.705	.707	.709	.711
1.8	.713	.715	.717	.719	.721	.723	.725	.726	.728	.730
1.9	.732	.734	.736	.738	.739	.741	.743	.745	.747	.748
2.0	.750	.752	.754	.755	.757	.759	.760	.762	.764	.765
2.1	.767	.768	.770	.772	.773	.775	.776	.778	.779	.781
2.2	.782	.784	.785	.787	.788	.790	.791	.793	.794	.796
2.3	.797	.798	.800	.801	.803	.804	.805	.807	.808	.809
2.4	.811	.812	.813	.815	.816	.817	.818	.820	.821	.822
2.5	.823	.824	.826	.827	.828	.829	.830	.832	.833	.834
2.6	.835	.836	.837	.839	.840	.841	.842	.843	.844	.845
2.7	.846	.847	.848	[illegible]	.850	.851	.852	.853	.854	.855
2.8	.856	.857	.858	.859	.860	.861	.862	.863	.864	.865
2.9	.866	.867	.868	.869	.870	.871	.872	.872	.873	.874
3.0	.875	.876	.877	.878	.878	.879	.880	.881	.882	.883
3.1	.883	.884	.885	[illegible]	.887	.887	.888	.889	.890	.890
3.2	.891	.892	.893	.893	.894	.895	.896	.896	.897	.898
3.3	.899	.899	.900	.901	.901	[illegible]	.903	.903	.904	.905
3.4	.905	.906	.907	.907	[illegible]	.909	.909	.910	.910	.911
3.5	.912	.912	.913	.913	[illegible]	.915	.915	.916	.916	.917
3.6	.918	.918	.919	.919	[illegible]	.920	.921	.921	.922	.923
3.7	.923	.924	.924	.925	[illegible]	.926	.926	.927	.927	.928
3.8	.928	.929	.929	.930	.930	.931	.931	.932	.932	.933
3.9	.933	.934	.934	.934	.935	[illegible]	.936	.936	.937	.937
4.0	.938	.938	.938	.939	.939	.940	.940	.941	.941	.941
4.1	.942	.942	.943	.943	.943	.944	.944	.944	.945	.945
4.2	.946	.946	.946	.947	.947	.947	.948	.948	.949	.949
4.3	.949	.950	.950	.950	.951	.951	.951	.952	.952	.952
4.4	.953	.953	.953	.954	.954	.954	.955	.955	.955	.956
4.5	.956	.956	.957	.957	.957	.957	.958	.958	.958	.959
4.6	.959	.959	.959	.960	.960	.960	[illegible]	.961	.961	.961
4.7	.962	.962	.962	.962	.963	.963	.963	[illegible]	.964	.964
4.8	.964	.964	.965	.965	.965	.965	.966	.966	.966	.966
4.9	.967	.967	.967	.967	.967	.968	.968	.968	.968	.969
5.0	.969	.969	.969	.969	.970	.970	.970	.970	.970	.971
5.1	.971	.971	.971	.971	.972	.972	.972	.972	.972	.973
5.2	.973	.973	.973	.973	.974	.974	.974	.974	.974	.974
5.3	.975	.975	.975	.975	.975	.976	.976	.976	.976	.976
5.4	.976	.977	.977	.977	.977	.977	.977	.977	.978	.978
5.5	.978	[illegible]	.978	.978	.979	.979	.979	.979	.979	.979
5.6	.979	.980	.980	.980	.980	.980	.980	.980	.981	.981
5.7	.981	.981	.981	.981	.981	.981	.982	.982	.982	.982
5.8	.982	.982	.982	.982	.983	.983	.983	.983	.983	.983
5.9	.983	.983	.984	.984	.984	.984	.984	.984	.984	.984

TIME FUNCTION (Three decimal places)

APPENDIX A

TABLE 6

THREE-PLACE TIME FUNCTIONS
FOR TIME UNITS FROM 0.00 TO 5.99

TIME FUNCTIONS

(PERCENTAGE DECIMAL)

FOR DETERMINATION OF TISSUE PRESSURE IN 5, 10, 20, 40, 80, 120, 160, 200 AND 240—MINUTE TISSUES DURING EXPOSURES UP TO 150 MINUTES

EXPOSURE TIME MINUTES	TISSUE HALF TIME (Minutes) 5	10	20	40	80	120	160	200	240
1	.129	.066	034	017	009	004	004	002	002
2	.242	.129	.066	.034	017	011	009	.007	004
3	.340	187	098	050	.026	017	.013	011	009
4	425	242	129	.066	.034	022	017	014	.011
5	.500	293	158	083	042	028	022	018	014
6	.564	340	187	098	050	034	026	021	.017
7	621	384	215	114	059	039	030	024	020
8	669	425	242	129	067	045	.034	027	022
9	712	463	268	144	075	050	037	031	025
10	750	500	293	158	.083	055	042	.034	.028
11	782	533	317	173	091	061	045	.038	.031
12	.811	.564	340	187	099	.066	050	041	.034
13	835	593	362	201	107	072	055	.044	036
14	857	621	384	215	114	078	059	.047	039
15	875	646	405	229	122	083	063	.051	042
16	.892	669	425	242	129	.088	.067	054	045
17	.906	692	445	254	137	093	071	057	047
18	.918	712	463	268	144	096	074	061	050
19	927	732	482	280	152	103	078	064	053
20	.937	750	500	293	158	108	084	067	.055
21	945	766	516	304	165	114	087	070	059
22	953	782	533	317	173	119	090	073	061
23	959	797	548	328	181	124	094	077	064
24	963	811	564	340	187	129	099	081	066
25	967	824	579	351	196	134	102	083	069
26	972	835	593	362	201	139	107	086	072
27	977	847	607	373	209	143	110	089	075
28	980	857	621	384	215	149	114	092	078
29	982	866	633	395	222	154	118	[illegible]	081
30	985	875	646	405	229	158	122	.099	.083
31		884	657	415	235	162	125	102	085
32		892	669	425	242	168	129	105	088
33		899	681	435	249	173	132	108	090
34		906	692	445	255	178	137	111	093
35		912	702	454	262	183	141	114	095
36		918	712	463	268	187	144	117	098
37		922	722	473	275	192	148	120	101
38		927	732	482	280	197	151	123	103
39		932	741	491	287	201	154	126	106
40		937	750	500	293	206	159	129	108
41		941	758	508	299	210	162	133	111
42		945	766	516	304	215	166	136	114
43		949	774	525	311	219	169	139	116
44		953	782	533	317	224	173	141	119
45		956	790	541	323	228	177	144	121
46		959	797	548	328	233	180	147	124
47		960	804	556	335	237	184	150	126
48		963	811	564	340	242	188	153	129
49		965	817	572	346	248	192	156	131
50		967	824	579	351	250	195	159	134
51		970	830	586	357	255	198	162	137
52		972	835	593	362	259	201	165	139
53		974	841	600	369	264	205	168	141
54		977	847	607	373	268	208	17	143
55		978	852	614	379	272	211	174	146
56		980	857	621	384	277	215	176	149
57		981	862	627	390	281	218	179	151
58		982	866	633	395	285	222	182	154
59		984	871	639	400	289	226	185	156
60		985	874	646	405	293	229	188	159
61			880	652	411	297	233	191	161
62			884	657	415	300	235	193	164
63			888	664	421	304	238	196	166
64			892	669	425	309	242	199	169
65			895	675	431	313	244	201	171
66			899	681	435	317	248	204	173
67			902	686	440	321	251	207	175
68			906	692	445	324	255	210	178
69			909	697	450	328	259	213	180
70			912	702	455	332	262	215	183
71			915	707	459	336	264	218	185
72			918	712	464	340	268	221	187
73			920	717	469	342	271	224	190
74			922	722	473	347	274	226	192
75			925	727	478	352	276	229	194

TABLE T

EXPOSURE TIME MINUTES	TISSUE HALF TIME (Minutes) 20	40	80	120	160	200	240
76	927	732	482	354	280	232	.197
77	930	736	487	359	284	235	199
78	932	741	491	362	287	237	201
79	934	745	495	368	289	240	203
80	937	750	500	373	293	242	206
81	939	754	505	374	296	245	208
82	941	758	508	377	299	247	[illegible]
83	943	763	512	381	302	250	[illegible]
84	945	766	516	384	305	253	215
85	947	770	521	387	308	256	217
86	949	774	524	[illegible]	310	258	219
87	951	778	528	395	313	261	222
88	953	782	533	399	317	263	[illegible]
89	955	786	537	402	319	266	[illegible]
90	956	790	541	405	323	268	229
91	957	794	545	408	325	271	231
92	959	797	550	411	328	273	233
93	959	797	554	415	332	275	235
94	960	804	557	4.9	334	278	237
95	962	807	561	423	337	281	[illegible]
96	963	811	565	425	340	283	[illegible]
97	964	814	569	428	342	285	245
98	965	817	573	431	346	288	248
99	966	820	576	435	348	291	249
100	967	824	580	439	352	293	250
101	968	826	584	442	355	[illegible]	253
102	970	830	[illegible]	445	357	298	255
103	971	832	591	448	[illegible]	301	257
104	972	835	594	451	363	303	259
105	973	838	597	455	365	305	[illegible]
106	974	841	601	458	368	307	[illegible]
107	976	844	605	461	371	310	[illegible]
108	977	847	608	463	374	312	[illegible]
109	977	849	611	466	377	314	[illegible]
110	978	852	615	469	379	317	272
111	979	854	618	472	381	[illegible]	[illegible]
112	980	857	622	476	384	[illegible]	[illegible]
113	980	859	625	479	[illegible]	[illegible]	[illegible]
114	981	862	628	482	390	[illegible]	[illegible]
115	982	864	631	484	392	329	[illegible]
116	982	866	634	487	395	[illegible]	[illegible]
117	983	[illegible]	[illegible]	491	[illegible]	[illegible]	[illegible]
118	984	870	640	494	400	[illegible]	[illegible]
119	984	873	644	497	403	338	[illegible]
120	985	875	647	500	405	340	[illegible]
121		877	650	503	407	[illegible]	[illegible]
122		880	[illegible]	506	[illegible]	[illegible]	[illegible]
123		882	656	509	[illegible]	[illegible]	[illegible]
124		884	[illegible]	512	416	[illegible]	[illegible]
125		886	662	515	418	[illegible]	[illegible]
126		888	665	517	421	354	[illegible]
127		890	668	[illegible]	424	356	[illegible]
128		892	670	523	426	[illegible]	[illegible]
129		894	673	525	428	[illegible]	[illegible]
130		895	676	528	431	363	[illegible]
131		898	679	531	433	[illegible]	[illegible]
132		899	682	533	436	367	[illegible]
133		900	685	536	438	370	[illegible]
134		902	687	539	440	372	[illegible]
135		904	690	542	443	374	[illegible]
136		906	693	545	445	376	[illegible]
137		908	695	547	447	378	[illegible]
138		909	698	550	450	[illegible]	[illegible]
139		910	701	552	452	[illegible]	[illegible]
140		912	703	555	455	384	[illegible]
141		913	705	557	457	387	[illegible]
142		915	708	560	459	389	[illegible]
143		916	711	562	462	391	[illegible]
144		918	713	565	464	393	340
145		919	715	567	466	395	342
146		920	718	570	469	[illegible]	[illegible]
147		920	720	572	471	399	[illegible]
148		922	723	575	474	401	347
149		924	725	577	476	403	[illegible]
150		925	728	580	478	405	[illegible]

APPENDIX B

ıble of Maximum Allowable Tissue Tensions (M) of Nitrogen for Various Half-
me Tissues

Depth of decompression stop

(ft)	10	20	30	40	50	60	70	80	90	100
(ft)	43	53	63	73	83	93	103	113	123	133
(min)	(M) (Feet of sea water equivalent)									
5	104	122	140	158	176	194	212	230	248	266
0	88	104	120	136	152	168	184	200	216	232
0	72	87	102	117	132	147	162	177	192	207
0	56	70	84	98	112	126	140	154	168	182
0	54	67	80	93	106	119	132	145	158	171
0	52	64	76	88	100	112	124	136	148	160
0	51	63	74	86	97	109	120	132	143	155
0	51	62	73	84	95	106	117	128	139	150
0	50	61	72	83	94	105	116	127	138	149

$\Delta M/\Delta 10$ feet depth

(min)	5	10	20	40	80	120	160	200	240
ft)	18	16	15	14	13	12	11.5	11	11

TABLE N   APPENDIX C

Table of Maximum Allowable Tissue Tension (M) of Helium for Various Half-time Tissues

Depth of decompression stop

D (ft)	10	20	30	40	50	60	70	80	90	100
A (ft)	43	53	63	73	83	93	103	113	123	133
H (min)	(M) (Feet of sea water equivalent)									
5	86	101	116	131	146	161	176	191	206	221
10	74	88	102	116	130	144	158	172	186	200
20	66	79	92	105	118	131	144	157	170	183
40	60	72	84	96	108	120	132	144	156	168
80	56	68	80	92	104	116	128	140	152	164
120	54	66	78	90	102	114	126	138	150	162
160	54	65	76	87	98	109	120	131	142	153
200	53	63	73	83	93	103	113	123	133	143
240	53	63	73	83	93	103	113	123	133	143

$\Delta M/\Delta 10$ feet depth

H (min)	5	10	20	40	80	120	160	200	240
ΔM (ft)	15	14	13	12	12	12	11	10	10

TABLE H APPENDIX D

Table of Maximum Allowable Tissue Tensions (M) of Inert Gas for Various Half Time Tissue (H) for Air Dives

D (ft)	10	20	30	40	50	60	70	80
A (ft)	43	53	63	73	83	93	103	113
h (min)	(M) (Feet of sea water equivalent)							
5	104	126	150	174	195	220	242	263
10	88	107	128	148	167	189	208	228
20	72	90	106	124	141	153	174	192
40	58	72	87	99	113	128	141	156
80	52	65	78	90	103	115	128	142
120	51	64	76	88	101	114	126	140

$M = 33 \left[(J) + r - 1.25 \right]$

$J = (S/r)^{10} = M/33 - (r - 1.25)$

S = Surfacing tissue ratio

r = Depth tissue ratio at stops

TABLE D APPENDIX E