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RESEARCH REPORT 4-56

CALCULATION OF AIR DECOMPRESSION TABLES

PROJECT NS185-005 SUBTASK 5 TEST 3

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ABSTRACT

This report presents the theory of air decompression in didactic form, including definitions, theory of exponential saturation, and theory of tissue ratios. The report provides a procedure for step-by-step calculation of decompression schedules, together with the necessary tables and worksheets. The discussion touches on other methods of calculation, on one use of this method, and on the probable validity of this method. The recommendations are for programming a computer and for using the report as a text.

FOREWORD

This project was originally established by the Bureau of Ships to provide decompression tables for repetitive dives. The original project outline is dated 16 December 1954.

Incidental to the programming of a computer to calculate repetitive diving decompression tables, it has become necessary to provide a step-by-step procedures for such calculations. Such a programming procedure can also serve as a text for instruction of students, if amplified by an exposition of the basic theories.

The procedure given in this report is not new. It is based primarily on a method outlined by Yarbrough in 1937, and ultimately on the method developed by Boycott, Damant, and Haldane in 1908.

Work on this report commenced in January of 1955. The manuscript was submitted 29 November 1955. This report is part of the Research Report series.

This is the first report for the project. It is an interim report. Future reports will cover the computer results and test dive results.

SUMMARY

PROBLEM

(1) Provide a step-by-step procedure for the calculation of air decompression tables.

(2) Provide a text on the theory of air decompression.

FINDINGS

(1) This report gives a step-by-step procedure for the calculation of air decompression tables.

(2) This report presents the theory of air decompression in didactic form, including definitions and basic theories.

RECOMMENDATIONS

(1) Program a computer to analyze tissue ratios for all dives in the U.S. Navy Standard Air Decompression Table (6.2 (1)).

(2) Program a computer to calculate repetitive diving tables, after satisfactory tissue ratios are established.

(3) Use this report as a text in the theory of air decompression.

(4) Revise this report or supersede it as a text when its weaknesses or flaws become apparent.

CONTENTS

1. OBJECT

1.1 Objectives

This report has two objectives:

(1) To provide a step-by-step procedure for the calculation of air decompression tables.

(2) To provide a text on the theory of air decompression.

1.2 Scope

1.2.1 This report does not consider all the possible variations in methods of calculating decompression tables. It presents a single procedure aimed at programming a digital computer for calculation of repetitive diving tables.

1.2.2 The "text" portion of this report is a simple version of the basic theory, given in didactic form. The text mentions some variations of the theory, but does not go into great detail.

2. DESCRIPTION

2.1 Background

2.1.1 Boycott, Damant, and Haldane first established a rational basis for prevention of decompression sickness in compressed air work. They formulated decompression tables based on exponential saturation of the body tissues with inert gas and on limiting tissue pressure ratios during ascent. These investigators published their hypothesis in 1908. They gave excellent coverage to the theories and to the experimental work substantiating the theories, but they did not publish the mechanics of the method which they used to calculate the decompression tables.

2.1.2 In 1937 Yarbrough compiled a procedure for the calculation of air decompression tables. For eighteen years this gauge and its revisions have served as the only available texts on the calculation procedure. The texts did not define all of the terms involved in the hypothesis, and did not clarify certain procedures in the calculation. The instructors have had to supply the omissions verbally from their own comprehension of the basic concepts. The resulting instruction has not always been satisfactory. The students have sometimes grasped the concepts and method, if at all, only by sheer determination.

2.1.3 The instructions given in the 1937 gauge are suitable for manual computations once the student understands the method. They are not precise or detailed enough for the programming of a computing machine. For adequate programming, every step of the complete sequence must be available in a didactic "yes-no" form.

2.1.4 The primary purpose of this report is to provide programming instructions for a computing machine. The procedure outlined in Part 3 (PROCEDURE) serves this purpose.

2.1.5 The secondary purpose of this report is to provide a text on the theory or air decompression. The remainder of Part 2 (DESCRIPTION) is such a text.

2.2 Definitions and symbols

2.2.1 DEPTH

(1) Depth (D) is the vertical distance below the surface at any phase of the dive (initial exposure or subsequent decompression stops).

(2) The units of depth are feet of salt water. In decompression calculations all pressures are expressed in feet of salt water, to eliminate conversion of units. Correction is not normally made for dives in fresh water, because the error is in the diver's favor.

2.2.2 ABSOLUTE DEPTH

(1) Absolute depth (A) is the absolute pressure at any depth (D), expressed in feet of salt water. For deep sea diving calculations the absolute depth (A) is always 33 feet greater than the actual depth (D).

(2) Under special conditions the absolute depth may have some other value. For example, the absolute depth in a mountain lake at 8000 feet is only about 25 feet greater than the actual depth. This variation can make the decompression for high-altitude dives considerably different from the decompression for sea-level dives.

2.2.3 OXYGEN PERCENTAGE DECIMAL

(1) The oxygen percentage decimal (x) expresses the oxygen content of the breathing medium during any phase of a dive. For open-circuit breathing it is exactly the oxygen content of the gas supply. For semi-closed and closed-circuit breathing it may be less.

(2) Analysis for oxygen content by laboratory means is generally the method for determining the oxygen percentage decimal. When subtracted from unity (1.00), the oxygen percentage decimal (x) gives the inert gas content of the breathing medium.

2.2.4 INERT GAS PERCENTAGE DECIMAL

(1) The inert gas percentage decimal (g) expresses the inert gas content of the breathing medium during any phase of a dive. for open-circuit breathing it is exactly the inert gas content of the gas supply. For semi-closed and closed-circuit breathing it may be greater because of the fall of oxygen percentage due to oxygen consumption.

(2) The inert gas percentage decimal (g) is commonly derived by subtracting the breathing medium oxygen percentage decimal (x) from unity (1.00). In the special case of air decompression

only, the oxygen content is disregarded, and the inert gas percentage decimal is taken as unity (1.00); however, the tissue ratios have corresponding special values. In other cases, the inert gas content of the breathing medium is given as a decimal ranging from 0.00 for pure oxygen, through 0.79 for air-equivalent mixtures, to greater values for lower oxygen content.

2.2.5 INERT GAS PARTIAL PRESSURE

(1) The inert gas partial pressure (N) represents the sum of the partial pressures of all gases in the breathing medium other than oxygen. The inert gas partial pressure (N) at any depth is derived by multiplying the absolute depth (A) by the inert gas percentage decimal (g).

(2) The inert gas partial pressure is generally handled as an entity, but is may represent the effects of more than one gas. For example, the inert gas content of air is handled as "79% nitrogen", although it actually includes 78% nitrogen and 1% argon. Special procedures may require handling two inert gases separately, as in the calculation of helium-oxygen decompression tables.

2.2.6 INITIAL TISSUE PRESSURE

(1) The initial tissue pressure (P) is the partial pressure of inert gas in a tissue at the start of any particular time interval.

(2) When there has been no dive within 12 hours prior to the dive under consideration, the initial tissue pressure for all tissues at the start of the dive is taken as the nitrogen partial pressure in air. For repetitive dives within a 12-hour period, the initial tissue pressure is taken as the nitrogen partial pressure in air plus the amount remaining in the tissues from the last dive. The amount remaining must be calculated for desaturation during the time interval on the surface.

(3) For each step in the decompression calculation, the final tissue pressure of one step becomes the initial tissue pressure of the next step.

2.2.7 DIFFERENTIAL PRESSURE

(1) The differential pressure (E) is the difference between the inert gas partial pressure (N) of the breathing medium and the initial tissue pressure (P). It represents the driving force which causes saturation or desaturation to take place.

(2) The numerical value of the differential pressure (E) is positive (+) if the inert gas partial pressure (N) is more

than the initial tissue pressure (P), indicating that the tissue gains inert gas. The value is negative (-) if the inert gas partial pressure less than the initial tissue pressure, indicating that the tissue loses inert gas.

2.2.8 SATURATION AND DESATURATION

(1) Saturation is the process of gaining inert gas during exposure to a positive differential pressure. "Complete saturation" is the state of balance occurring when the final tissue pressure (Q) equals the inert gas partial pressure (N) in the breathing medium.

(2) Desaturation is the process of losing inert gas during exposure to a negative differential pressure. "Complete desaturation" is the state of balance occurring when the final tissue pressure (Q) equals the inert gas partial pressure (N) in air at the surface.

2.2.9 TISSUE PRESSURE CHANGE

(1) 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 the differential pressure (E) and the time function (f) for the interval. It is algebraically positive (+) or negative (-) according to the sign of the differential pressure.

(2) The tissue pressure change represents the saturation (+) or desaturation (-) occurrring during an exposure.

2.2.10 FINAL TISSUE PRESSURE

(1) The final tissue pressure (Q) is the partial pressure of inert gas in a tissue at the end of a time interval. It is the sum of the initial tissue pressure (P) and the tissue pressure change (S).

(2) The final tissue pressure (Q) for one interval becomes the initial tissue pressure (P) for the next interval calculated.

2.2.11 TIME INTERVAL

(1) The time interval (t) is the duration in minutes of any specific phase of the dive under consideration. These phases are usually taken as: (1) the exposure (descent and bottom time together); (2) the ascent; (3) the first stop; (4) each of the intermediate stops; (5) the last stop; and, in repetitive dives, (6) the surface interval.

(2) In practice, the exposure time interval includes both time of descent and time at depth. However, the calculations always assume instantaneous descent to the diving depth, and there is no separate calculation for descent time.

(3) The ascent time interval depends on the depth of the first stop and the rate of ascent. In standard diving practice the rate is 25 feet a minute or less. In scuba diving the standard rate may be much slower than the actual rate. When analyzing cases of decompression sickness from scuba diving, use the actual rate of ascent if known.

(4) The time interval at each stop depends on the length of time required to desaturate the "controlling tissue" to a final tissue pressure (Q) equal to or less than the maximum tissue pressure (M) for the next stop. (See articles 2.2.19, 2.2.10, and 2.2.16).

(5) The surface time interval must be considered when it is less than 12 hours (720 minutes) to the next dive. The tissues continue to desaturate while on the surface. The final tissue pressures at the end of the surface interval are the initial tissue pressures for the next exposure.

2.2.12 TISSUE HALF TIME

(1) 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. Theoretically this time interval is always the same for a given tissue regardless of the magnitude of the exposure differential pressure.

(2) In calculations, tissues are designated by their half times. The relative term "fast tissue" is applied to a tissue with a short half time, and "slow tissue" is applied to a tissue with a long half time.

(3) The body probably consists of an infinite number of tissues with half times ranging from zero to 120 minutes. For calculations the range of tissues may be "sampled" in either arithmetical or geometrical progression of the half times. Because of the exponential nature of the basic theory, geometrical progression is satisfactory and minimizes the number of samples. For air decompression calculations, samples are usually taken at least on the 20-minute, 40-minute, and 80-minute tissues. In a complete analysis samples are also taken on the 5-minute, 10-minute, and 120-minute tissues. For helium decompression calculations, samples are usually taken arithmetically on the 5, 10, 20, 30, 40, 50, 60 and 70-minute tissues. Apparently because of the faster rate of saturation with helium, tissue half times for helium do not extend beyond the 70-minute tissue.

2.2.13 TIME UNIT

(1) For a given time interval (t) in a tissue with a specific half time (h) the time unit (u) is the number of half times in that interval. It is therefore the ratio (t/h) of the time interval to the half time of the tissue in question, and is dimensionless.

(2) In a given time interval (t), the time unit (u) is different for each tissue half time (h) being considered. Normally ranging from 0.000 to 6.000, the numerical value of the time unit is the quotient of the time interval (t) divided by the half time (h).

(3) The time unit (u) is related to the time function (f). In some methods of calculation it is used to find the time function from a tabulation against time units. In other methods the time function is tabulated against time intervals for specific tissue half times, so that the time unit does not appear in the calculations.

2.2.14 TIME FUNCTION

(1) When a differential pressure (E) acts on a given tissue, the initial tissue pressure (P) changes by a specific amount (S) in any given time interval (t). The ratio of the amount of change (S) to the differential pressure (E) is a dimensionless decimal called the "time function" (f).

(2) The total amount of change (S) increases as the time interval (t) lengthens, so that the time function (f) also increases with time. Its value varies from 0.000 to 1.000 in a specific relation to the time unit.

(3) Normally the time function (f) may be obtained from a tabulation of the decimal against time units (u), or from tabulations of the decimal against time intervals (t) for various tissue half times (h).

(4) If no tabulation is available, the time function can be calculated from the following formula:

$$f - 1 - 1/2^{u}$$

where f - time function (dimensionless)

u - time unit (dimensionless)

(5) Since the time function (f) is the ratio of the tissue pressure change (S) to the exposure differential pressure (E), it can be used for two purposes.

(5.1) Multiplying the exposure differnetial pressure by the time function for an interval gives the tissue pressure change:

$$S - fE$$

(5.2) During decompression, a certain amount of tissue pressure change must occur in the controlling tissue at each stop. Dividing the required change (S) by the exposure differential pressure (E) gives a time function (f) directly related to the time interval (t) required at each stop. This division is the basis for all calculations of decompression stop time.

2.2.15 NEXT ABSOLUTE PRESSURE

(1) In decompression, the absolute pressure (B) at the <u>next</u> stop becomes important. It determines the maximum tissue pressures for that stop. The tissue pressures for the stop under consideration must fall to or below the maximum tissue pressure for the next stop before the tissue can safely ascend to that depth.

(2) For the exposure conditions the next absolute pressure (E) is determined by dividing the final tissue pressure (Q) by the tissue ratio (r) for each tissue and selecting the greatest value.

(3) For all decompression stops the next absolute pressure (B) is 10 less than the present absolute depth (A).

2.2.16 MAXIMUM TISSUE PRESSURE

(1) The maximum tissue pressure (M) is the greatest partial pressure of inert gas in a specific tissue which will not cause bubbles to form in the tissue at a given absolute pressure. It is found by multiplying the part absolute pressure (B) by the tissue ratio (r).

(2) The maximum tissue pressure governs decompression. The tissue pressures for the stop under consideration must fall to or below the maximum tissue pressures for the next stop before the tissues can safely ascend to the next stop.

2.2.17 SUPERSATURATION

(1) Supersaturation is an unstable state occurring when the initial tissue pressure (P) is equal to the maximum tissue pressure (M) allowable at any given absolute depth.

(2) If the initial tissue pressure (P) exceeds the maximum tissue pressure (M) the tissue will release inert gas in the form of bubbles until the tissue pressure falls to the maximum tissue pressure.

(3) When a tissue is in supersaturation, the initial tissue pressure (P) is always greater than the inert gas partial pressure (N). Under these conditions the differential pressure (E) is algebraically negative, and the tissue will lose inert gas by dissolution.

2.2.18 TISSUE RATIO

(1) The tissue ratio (r) is the ratio (M/B) of the maximum tissue pressure to the next absolute pressure.

(2) The tissue ratio (r) is <u>not</u> dimensionless. The units are "feet of partial pressure per foot of absolute pressure".

(3) Tissue ratios are determined empirically by exposing subjects to pressure. When they develop decompression sickness after a specific exposure and subsequent decompression (or lack of decompression), calculation of tissue pressures throughout the dive ultimately yields an indication of the critical tissue ratio.

(4) The concept of tissue ratio first arose from the work of Boycott, Damant, and Haldane. They found that goats exposed for long periods to air at two atmospheres could surface directly to one atmosphere with no decompression. When the exposure pressure was much over two atmospheres, the animals developed decompression sickness. From these experiments the investigators inferred that the human body could withstand a tissue-to-absolute pressure ratio of two to one without risking decompression sickness. Unfortunately for clarity, the original report did not consider the actual partial pressure in the tissue. Instead, it indicated that the tissues would equilibrate with the total (absolute) pressure. This assumption leads naturally to a "tissue ratio" of 2:1.

(5) In actual fact for saturation with air at two atmospheres, the tissue pressure equilibrates with about 1.58 atmospheres of inert gas partial pressure (79% nitrogen at 2 atmospheres). The true critical ratio is therefore 1.58:1.

(6) In the case of air decompression only, the procedure assumes that air is 100% nitrogen, so that the calculations are for equilibration with the absolute pressure. Use of a "total pressure" tissue ratio therefore is satisfactory. Note that there is no safety factor in this procedure unless the tissue ratio is taken as the "partial pressure" value. When coupled with the assumption that air is 100% nitrogen, the true value is very restrictive in decompression requirements. It is never used in standard air calculations.

(7) Later work indicated that the "total pressure" tissue ratio of 2:1 was too low for very fast tissues and too high for very slow tissues. Because of the empirical basis for tissue ratios

no one has established definite, unchallenged values to use for air decompression calculations.

(8) In much of the early analysis work to establish tissue ratios, the slowest tissue considered was the 75-minute tissue. Subsequent research indicates the existence of 120-minute tissues for air. Careful consideration of this very slow tissue shows that is has an important effect in long, deep dives. Failure to consider its effect may lead to selection of an artificially low value of tissue ratio for the next faster tissues.

(9) Some authorities feel that tissue ratio may vary somewhat with depth, becoming smaller as depth increases. There is at least one mathematical analysis supporting this hypothesis, and the variation may be real. However, the apparent variation may occur because of empirical adjustments in tissue ratio to account for a slow tissue which has not been considered.

(10) In the calculation of decompression tables for helium a tissue ratio of 1.70 is applied to every tissue. In the confusion with "total pressure" ratios for air, this looks like a very low value. It is 0.30 less than the "standard" air ratio of 2.00, and 0.05 less than the lowest air ratio of 1.75. However, the procedure considers tissue saturation to equilibration with inert gas partial pressure throughout. The value of 1.70 is therefore used as a true partial-to-absolute pressure tissue ratio. Its actual value as a "total pressure" ratio is 2.15 (1.70/0.79), and it is effectively 0.15 greater than the "standard" air ratio. This high effective value of tissue ratio may account for some of the cases of decompression sickness which occur while the diver is still decompressing for a helium dive.

2.2.19 CONTROLLING TISSUES

(1) At the end of bottom time each tissue has a different value of depth above which it cannot ascend without bubble formation. The controlling tissue for ascent is the tissue which must stop at the greatest depth to avoid bubble formation.

(2) At a given decompression stop some initial tissue pressures (P) will be greater than the corresponding maximum tissue pressures (M) 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. The controlling tissue for the given stop is the tissue which requires the longest time to desaturate to the maximum tissue pressure at the next stop.

2.2.20 SYMBOL SUMMARY

Symbol	Description	Units	Reference
D	diving depth	feet	(2.2.1)
A	absolute depth	feet	(2.2.2)
x	oxygen percentage decimal	dimension-less	(2.2.3)
g	inert gas percentage decimal	dimension-less	(2.2.4)
N	inert gas partial pressure	feet	(2.2.5)
P	initial tissue pressure	feet	(2.2.6)
E	differential pressure	feet	(2.2.7)
S	tissue pressure change	feet	(2.2.9)
Q	final tissue pressure	feet	(2.2.10)
t	time interval	minutes	(2.2.11)
h	tissue half time	minutes	(2.2.12)
u	time unit	dimension-less	(2.2.13)
f	time function	dimension-less	(2.2.14)
B	next absolute pressure	feet	(2.2.15)
M	maximum tissue pressure	feet	(2.2.16)
r	tissue ratio (partial-to-absolute)	feet per foot	(2.2.18)

2.3 Theory of Exponential Saturation

2.3.1 Decompression is necessary for dives on air beyond 30 feet. The need arises when tissue saturation with inert gas reaches the point that the tissue can no longer surface directly without bubble formation. Haldane's theory of exponential saturation yields a basis for calculation of tissue pressures throughout the course of a dive.

2.3.2 Final tissue pressure (Q) at the end of any time interval is quite simply the sum of the initial tissue pressure (P) at the start of the interval and the tissue pressure change (S) during the interval.

$$Q = P + S$$

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

$$P_2 = Q_1$$

2.3.4 Tissue pressure change (S) during an interval depends on the existence of a differential pressure (E). The amount of change is an exponential function (f) of the time unit. The tissue pressure change (S) itself is the product of the time function (f) and the diferential pressure (E).

$$S = (f)(E)$$

2.3.5 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.

$$E + (N - P)$$

2.3.6 The time function (f) is a specific exponential function of the time unit (U).

$$f = (1-1/2^u)$$

2.3.7 The time unit (U) is the ratio of the time interval (t) to the half time (h).

$$u = (t/h)$$

2.3.8 The entire theory of exponential tissue saturation can be expressed in a single equation expanded from 2.3.2 above.

$$Q = P + S$$

$$= P + fE$$

$$= P + (1 - \frac{1}{2^u})E$$

$$= P + (1 - \frac{1}{2^u})(N - P)$$

$$= P + (1 - \frac{1}{2^{t/h}})(N - P)$$

$$\boxed{Q = P + 1 - 2^{-\left(\frac{t}{h}\right)} (N - P)}$$

2.4 Theory of Tissue Ratios

2.4.1 A tissue can hold some amount of dissolved inert gas in supersaturation. The amount depends on the absolute pressure around the tissue. The ratio of maximum tissue pressure (M) to absolute depth (A) is generally considered to be a constant for any specific tissue.

2.4.2 If a tissue is at the point of supersaturation and the absolute pressure falls (as during ascent), the tissue releases inert gas as bubbles. The tissue continues to form bubbles until it reaches a new state of supersaturation in balance with the lower absolute pressure.

2.4.3 A tissue gains inert gas during a dive. At the end of the dive the tissue can safely ascend a certain distance. It then reaches supersaturation and cannot ascend farther until it loses some of the inert gas. Haldane's theory of tissue ratio furnished a tool for determining:

(1) The depth at which the first decompression stop must be made.

(2) The length of time for the first and all subsequent stops.

2.4.4 The least absolute pressure (B) to which a tissue can ascend depends on the tissue pressure. The final tissue pressure (Q) at the end of ascent must not exceed the maximum tissue pressure (M) for the first stop.

2.4.5 If ascent is reasonably fast, the tissue pressure at the end of ascent will be approximately the final tissue pressure at the end of bottom time. Dividing the final bottom tissue pressure (Q) by the tissue ratio (r) yields an approximation of the least absolute pressure (B) for the first stop.

$$B \cong Q/r$$

2.4.6 The approximate value is converted to depth and then increased to an even 10-foot value for the trial first stop. During ascent to the trial first stop, the controlling tissue may lose enough inert gas to permit ascent to the next stop. Other tissues may gain enough gas to take control and limit ascent to the trial first stop or to some greater depth. More than one trial calculation for ascent may be necessary before the first stop is definitely established.

2.4.7 At each decompression stop the controlling tissue determines the time interval for the stop. The controlling tissue pressure must fall to or below the maximum pressure allowable for that tissue at the next stop before all tissues may ascend to that stop.

$$Q \leq M$$

2.4.8 The tissue pressure change (S) required at a stop is at least the difference between the initial tissue pressure (P) and the maximum tissue pressure (M) at the next stop.

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

2.4.9 The differential pressure (E) for the controlling tissue at the given stop is the difference between the inert gas partial pressure (N) and the initial tissue pressure (P).

$$E = N - P$$

2.4.10 The algebraic sign for both the required tissue pressure change (S) and the acting differential pressure (E) is 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 the given stop.

$$f_{min} = (S_{min})/E$$

2.4.11 The least time function (f_{min}) corrosponds to some minimum time unit (u_{min}) and to some minimum time interval (t_{min}) for the controlling tissue half time (h). The minimum time interval is usually not an integral number of minutes. If not, it is increased to an integral value, producing a new time function. Final pressures in all tissues are then calculated for the new time interval.

$$Q = P + S$$

2.4.12 The controlling tissue is not always apparent. A fast tissue which requires a large change may lose enough inert gas in a short time interval. A slow tissue which requires a small change may not lose enough gas in the same interval. Selecting the controlling tissue is a matter of experience and judgment. If the wrong tissue is chosen, the correct tissue will have a calculated final tissue pressure (Q) greater than the maximum pressure (M) allowable for that tissue at the next stop. The given stop must be recalculated for the time required to desaturate the correct tissue.

2.4.13 Control generally shifts from the fast tissues to the slower tissues during decompression. During the deeper stops the slow tissues frequently have positive differential pressures, and they continue to gain inert gas at these stops. Failure to desaturate eventually forces such tissues into control at the shallower stops.

2.5 Time function tables

2.5.1 It is possible to calculate the time function directly from the time unit or from the time interval, and the "slide rule" method does so. Other methods use tabulations of the time function, either against time units or against time intervals in specific tissues.

2.5.2 Table U is a tabulation of time functions (f) against time units (u). The time functions are given to three decimal places, and the time units are given to two decimal places. The left-hand column shows the integer and 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.

2.5.3 Table T is the most common tabulation used for air decompression calculations. The left-hand column in each section shows the time interval in minutes. The other columns are headed by appropriate tissue half times, and show the corresponding time function.

2.5.4 The time unit tabulation is more versatile. It can be used for any tissue half time. The time interval tabulation is easier to use, but is limited to the tissue half times shown.

2.6 Decompression calculation worksheet

2.6.1 Manual calculation of decompression is tedious by any procedure. All methods require handling several tissues simultaneously. Some methods provide shortcuts for various steps, but the basic principles do not change.

2.6.2 Although laborious, calculation of decompression is simple when the entire dive is divided into several steps. The usual steps are:

(1) Exposure

(2) Trial first stop and ascent

(3) Analysis for correct first stop

(4) First stop

(5) Succeeding stops

(6) Surface interval.

2.6.3 The form shown as figure 1 can be used to calculate decompression for 4 tissues simultaneously. It is divided into five sections. The top section is for ambient conditions for any phase of the dive. The other 4 sections are for internal conditions for any phase of the dive. The sections are divided into vertical columns headed by the appropriate phase.

2.6.4 The top section is divided into four lines.

(1) Line D is for the depth in feet.
(2) Line A is for the absolute depth.
(3) Line N is for the inert gas partial pressure.
(4) Line t is for the time interval.

2.6.5 The other sections are divided into seven lines.

(1) Line u is for the time unit.
(2) Line f is for the time function.
(3) Line E is for the differential pressure.
(4) Line P is for the intial tissue pressure.
(5) Line S is for the tissue pressure change.
(6) Line Q is for the final tissue pressure.
(7) Line M is for the maximum allowable tissue pressure.

2.6.6 The top section has a special box (g) for the inert gas percentage decimal. Under normal conditions this value will apply throughout the calculations. In special cases (such as shifting to oxygen during decompression) the value may change.

2.6.7 The other sections have two special boxes.

(1) Box h is for the tissue half time. The half time does not change during calculation.
(2) Box r is for the tissue ratio. The tissue ratio may change during calculation by certain methods, usually only during surfacing.

3. PROCEDURE

3.1 General

3.1.1 The worksheet described in Section 2.6 and shown as figure 1 is necessary for this particular procedure. (It is usable for other methods).

3.1.2 Individual values in a column are designated by the term "line" together with the appropriate symbol underscored ("line Pn", "line E"). Columns are designated by the column heading ("exposure", "ascent"). Special values governing a section are designated by the term "box" together with the appropriate symbol underscored ("box r", "box h").

3.2 Preliminery

3.2.1 Enter the exposure conditions in the top section.

(1) Insert inert gas percentage decimal in box g.
(2) Insert diving depth in feet on line D for exposure.
(3) Calculate absolute depth.

(3.1) Add 33 to line D.
(3.2) Insert on line A for exposure.

(4) Calculate inert gas partial pressure.

(4.1) Multiply line A by box g.
(4.2) Insert on line N for exposure.

(5) Insert exposure time in minutes on line t for exposure.

3.2.2 Select appropriate tissue conditions.

(1) Insert tissue half time in box h.
(2) Insert tissue ratio in box r.

3.2.3 For each tissue under consideration, perform the calculations outlined in the following sections.

3.3 Exposure (Descent and Botton Time)

3.3.1 Calculate the time unit.

(1) Divide line t (at top of column) by box h.
(2) Insert on line u.

3.3.2 Calculate the initial pressure.

(1) Multiply 33 by box g.
(2) Insert on line P.

3.3.3 Find the time function.

(1) Enter table U (appendix) with time unit form line u.
(2) Select corresponding time function.
(3) Insert on line f.

3.3.4 Calculate the differential pressure.

(1) Subtract line P from line N.
(2) Insert on line E.
(3) Affix proper algebraic sign.

(3.1) Plus (+) if line N is greater than line P.
(3.2) Minus (-) if line N is smaller than line P.

3.3.5 Calculate the tissue pressure change.

(1) Multiply line E by line f.
(2) Insert on line S.
(3) Affix same algebraic sign as line E.

3.3.6 Calculate the final tissue pressure.

(1) Add line S to line P algebraically.
(2) Insert on line Q.

3.3.7 The final tissue pressure for the exposure is the initial tissue pressure for the ascent. Transfer line Q for the exposure to line P for the ascent.

3.4 Trial First Stop and Ascent

3.4.1 Find the trial first stop.

(1) Divide line P in ascent column by box r (for each tissue).
(2) Subtract 33 from highest value obtained.
(3) Increase result to next greater even value of 10.
(4) Insert on line D for first stop.

3.4.2 Calculate the average depth during ascent.

(1) Subtract line D for first stop from line D for exposure.
(2) Divide difference by 2.
(3) Add result to line D for first stop.
(4) Insert on line D for ascent.

3.4.3 Claculate the average absolute depth during ascent.

(1) Add 33 to line D.
(2) Insert on line A.

3.4.4 Calculate the average inert gas partial pressure during ascent.

(1) Multiply line A by box g.
(2) Insert on line N.

3.4.5 Calculate the time of ascent.

(1) Subtract line D for first stop from line D for exposure.
(2) Divide difference by 25.
(3) Select nearest whole number.
(4) Insert on line t.

3.4.6 Calculate the final tissue pressure in each tissue at the end of ascent. Follow thw appropriate steps in Section 3.3 (Exposure).

(1) Calculate the time unit (3.3.1).
(2) Find the time function (3.3.3).
(3) Calculate the differential pressure (3.3.4).
(4) Calculate the tissue pressure change (3.3.5).
(5) Calculate the final tissue pressure (3.3.6).

3.5 Analysis for Correct First Stop

3.5.1 Analyze the final tissue pressures for ascent, to determine if the trial first stop is the correct first stop.

(1) The first stop must not be too shallow for any tissue. The trial first stop is seldom too shallow. However, it may be if a slow tissue gains a large amount of inert gas during ascent.

(2) The first stop can be deeper than is required for all tissues except one. If it is deeper than necessary for every tissue under consideration, the trial first stop should be shallower. The shallower first stop provides a greater differential pressure and reduces the time interval required at the stop. The trial first stop is frequently "too deep", because the fast tissues generally lose large amounts of inert gas during ascent.

3.5.2 Check whether the trial first stop is too shallow.

(1) Multiply line A for the first stop by box r.
(2) If line Q for ascent is greater in any tissue, the trial first stop is too shallow.

3.5.3 If the trial first stop is too shallow, find the proper stop.

(1) Divide line Q for ascent by box r.
(2) Subtract 33 from the highest value obtained.
(3) Increase the result to the next greater even value of 10.
(4) Insert on line D for the first stop.
(5) Repeat steps 3.4.2 through 3.4.6.
(6) Repeat step 3.5.2.

3.5.4 If the trial first stop is not too shallow, check whether it is deeper than is required for all tissues.

(1) Subtract 10 from line A for the first stop.
(2) Multiply by box r.
(3) Insert on line M for the first stop.
(4) If line Q for ascent is smaller in every tissue, the trial first stop is too deep (3.5.1 (2)).
(5) If line Q for ascent is greater in at least one tissue, the trial first stop is not too deep.

3.5.5 If the trial first stop is deeper than necessary, find the proper stop.

(1) Repeat step 3.5.4, subtracting 10 from line A until line Q for ascent is greater for at least one tissue.
(2) Subtract 33 from the new value of line A.
(3) Insert on line D for the first stop.
(4) Repeat steps 3.4.2 through 3.4.6.
(5) Repeat steps 3.5.2 through 3.5.5 as necessary.

3.5.6 If the trial first stop is not too shallow (3.5.2) and not too deep (3.5.4), it is the correct stop for all tissues. The final tissue pressure for the last ascent calculated is the initial tissue pressure for the first stop. Transfer line Q for the ascent to line P for the first stop.

3.6 Time interval at first stop

3.6.1 Determining the time interval at each stop is the most important part of the decompression calculations. The objective is to determine the minimum time that the tissues must all spend at one stop before the controlling tissue (2.2.19) can ascend to the next stop.

3.6.2 The top section should already have values of depth on line D and absolute depth on line A. Calculate the inert gas partial pressure.

(1) Multiply line A by box g.
(2) Insert on line N.

3.6.3. Calculate the differential pressure.

(1) Subtract line P from line N.
(2) Insert on line E.
(3) Affix proper algebraic sign.

(3.1) Plus (+) if line N is greater than line P.
(3.2) Minus (-) if line N is smaller than line P.

3.6.4 Each tissue section should already have the value of initial tissue pressure on line P. Determine the maximum allowable tissue pressure.

(1) Multiply line A for the next stop by box r.
(2) Insert on line M.

3.6.5 Determine if further calculations are necessary for the faster tissues. Drop a tissue from further consideration if it meets all of the following conditions.

(1) There is no faster tissue under calculation.
(2) Line E has a minus (-) sign.
(3) Line M is greater than line P.

3.6.6 Select the controlling tissue. The steps given below are mechanical. Experienced judgment can dictate the proper choice without following these steps for all tissues. These operations must be performed for the controlling tissue.

(1) Subtract line P from line M.
(2) Divide by line E.
(3) Insert lightly on line f.

(4) Enter table U with line f.
(5) Select the corresponding value of time unit.
(6) Multiply by box h.
(7) Raise the largest value for any tissue to the next larger whole number.
(8) Insert on line t.
(9) Place a box around line Q for the tissue which determined the value of line t. This is the controlling tissue, and the value of line t is the required time interval at the stop.

3.6.7 Calculate the final tissue pressure in each tissue at the end of the first stop. Follow the appropriate steps in Section 3.3 (Exposure).

(1) Calculate the time unit (3.3.1).
(2) Find the time function (3.3.3).
(3) Calculate the tissue pressure change (3.3.5).
(4) Calculate the final tissue pressure (3.3.6).

3.6.8 Check line Q against line M, to be sure of the controlling tissue.

(1) Line Q must be equal to or smaller than line M, for all tissues.
(2) If line Q is larger than line M for any tissue, the selection of the controlling tissue was in error.

    (2.1) Repeat step 3.6.6 for the slowest tissue in which line Q is excessive.
    (2.2) Repeat steps 3.6.7 and 3.6.8 for all tissues.

3.6.9 If line Q is equal to or smaller than line M, for all tissues, transfer line Q for this stop to line P for the next stop.

3.7 Time intervals at succeeding stops

3.7.1 The remainder of the calculations are performed to determine the time intervals required at successive 10-foot stops to the surface. The procedure is similar to Section 3.6 (Time interval at first stop).

3.7.2 Check the depth of the stop.

(1) Subtract 10 from line D for the preceding stop.
(2) Compare with line D for this stop.

3.7.3 Check the absolute depth.

(1) Add 33 to line D for this stop.
(2) Compare with line A.

3.7.4 Determine the time interval and final tissue pressures. Follow the appropriate steps in Section 3.6.

(1) Calculate the inert gas partial pressure (3.6.2).
(2) Calculate the differential pressure (3.6.3).
(3) Calculate the maximum tissue pressure (3.6.4).
(4) Drop any tissues possible (3.6.5).
(5) Select the controlling tissue (3.6.6).
(6) Calculate the final tissue pressures (3.6.7).
(7) Check the controlling tissue (3.6.8).

3.7.5 The final tissue pressures for this stop are the initial tissue pressures for the next stop. Transfer line Q for this stop to line P for the next.

3.8 Surface interval

3.8.1 Calculation of the surface interval is necessary in the analysis of repetitive dives, in order to determine the amount of tissue pressure at the start of succeeding dives. The procedure is identical to that for Section 3.3 (Exposure), except that the initial tissue pressures are the final tissue pressures for the last stop of the preceding dives. (All tissues must have been calculated throughout the preceding dive (3.6.5)).

3.8.2 Establish the initial conditions.

(1) Transfer line Q for the 10-foot stop in line P in the next column.
(2) Insert a zero on line D.
(3) Insert 33 on line A
(4) Multiply line A by 0.79 or 1.00 (as appropriate for air, regardless of box g).
(5) Insert on line N.
(6) Insert the surface interval on line t.

3.8.3 Calculate the final tissue pressure in each tissue at the end of the surface interval. Follow the appropriate steps in Section 3.3. (Exposure).

(1) Calculate the time unit (3.3.1).
(2) Find the time function (3.3.3).
(3) Calculate the differential pressure (3.3.4).
(4) Calculate the tissue pressure change (3.3.5).
(5) Calculate the final tissue pressure (3.3.6).

3.8.4 The final tissue pressure for the surface interval is the initial tissue pressure for the exposure in the next dive. Transfer line Q for the surface interval to line P in the exposure column on a new worksheet.

3.9 Repetitive dives

3.9.1 Calculations for the succeeding dives are identical to those for the first dive, except for the determination of initial pressure in the exposure. Repeat Sections 3.3.6 through 3.8, omitting step 3.3.2. Except for the last dive of a series, also omit step 3.6.5.

3.9.2 In the case of general repetitive diving tables, the initial tissue pressure for the surface interval is not the final tissue pressure for the preceding dive. Instead, all tissues are assumed to reach the surface with the maximum tissue pressure allowable at the surface. Under this assumption, a repetitive table depends only on the surface interval and not on the preceding dive. This condition minimizes the number of tables needed for repetitive dives. Since the tissue pressures for the preceding dive do not affect the calculations for the next dive, step 3.6.5 may be taken for all dives.

4. RESULTS

4.1 Decompression tables

4.1.1 After completing the calculations for the 10-foot stop, tabulate the decompression data on a form similar to figure 2.

4.1.2 For each set of calculations list the depth, time, and controlling tissue as appropriate.

(1) For the dive (exposure) show the depth and time.
(2) For the ascent show the time and the tissue controlling ascent.
(3) For the decompression stops show the depth, time, and controlling tissue. Place the last stop in the right-hand column and place the others to the left in sequence.
(4) For the total ascent show only the time, indicating the sum of the time of ascent and time at stops.
(5) For the surface interval show the time preceding this dive.

4.1.3 List the results first by increasing value of exposure depth and second by increasing value of exposure time.

4.2 General repetitive tables

Group the tables according to the increasing value of surface interval preceding the dive.

5. DISCUSSION

5.1 Other methods

5.1.1 Several other methods can be used to calculate decompression tables. Some are simpler than the procedure given in this report. All of those based on Haldane's theories give the same results for the same tissue samples and ratios.

5.1.2 The classic tissue samples for air decompression are the 5, 10, 20, 40, and 75-minute tissues. The modern tissue samples are usually the 20, 40, 80 and 120-minute tissues.

5.1.3 The "slide-rule" method determines the time function as an exponential of the natural base of logarithms (e). For convenience the exponential constant is taken as 0.04, 0.02, 0.09 and 0.006. These values correspond approximately to tissue half times of 17, 35, 69 and 115 respectively.

5.2 Analysis for tissue ratios

5.2.1 When a case of decompression sickness results from a specific decompression schedule, an analysis of the dive may show which tissues were "responsible".

5.2.2 The procedure is similar to that given in Part 3.

(1) Drop the steps for the determination of the trial first stop and the controlling tissues.
(2) Use the actual rate of ascent, if known.
(3) Calculate tissue pressures for the actual stop depths and times.

5.2.3 Analyze for tissue ratios.

(1) Divide the initial pressure at each stop by the absolute pressure. The quotient is a "tissue ratio".
(2) Compare this value with the established empirical values. Those tissues with higher values are the likely "offenders".

5.3 Validity

5.3.1 The procedure given in this report is valid for the Haldane theories as given in Sections 2.3 and 2.4.

5.3.2 Both the multiple tissue theory and the half-time exponential saturation theory have come under fire because the resultant decompression schedules are not always satisfactory. This is particularly true of the schedules for long, deep dives. However, no other theory has yet produced comparably satisfactory decompression schedules with such a low overall incidence of decompression sickness.

5.3.3 Some of the apparent disagreement between theory and actuality may stem from poor parameters rather than basic flaws.

(1) Both the U.S. Navy Standard Air Decompression Table and the U.S. Navy Air Saturation Table were calculated for tissue half times of 75 minutes and less. Consideration of a 120-minute tissue certainly makes some difference, particularly in long, deep dives.

(2) The empirical values of tissue ratio are not well specified.

(2.1) The Standard Air Table uses an absolute pressure ratio of 2.8:1 for the 20-minute tissue down to 150 feet, and then shifts to 2.45:1 for some of the longer and deeper dives.

(2.2) The same table uses 2:1 for the 40 and 75-minute tissues down to 185 feet, and then shifts to 1.75:1 for some of the longer and deeper dives.

(2.3) The Air Saturation Table uses 2:1 for all tissues.

5.3.4 In view of the general adequacy of the Haldane theories, the procedure given in Part 3 is as satisfactory a method as any other for the calculation of decompression schedules. The parameters require careful attention and judicious selection.

6. CONCLUSIONS

6.1 Conclusions

(1) This report provides a satisfactory procedure for the calculation of air decompression tables (5.3.4).

(2) This report provides a text on the theory of air decompression (Part 2).

6.2 Recommendations

It is recommended that:

(1) This report be used to program a computing machine to analyze tissue ratios for all dives in the U.S. Navy Standard Air Decompression Table, for 5-minute increments of tissue half time from the 5-minute tissue through the 75-minute tissue, and for 10-minute increments from the 80-minute tissue through the 120-minute tissue.

(2) This report be used to program a computing machine to calculate repetitive diving tables, after satisfactory tissue ratios are established.

(3) That this report serve as a text for the instruction of students in the theory of air decompression.

(4) That this report be revised or superseded as a text when its weaknesses or flaws become apparent.

7. FIGURES AND APPENDICES

7.1 Figures

7.1.1 Figure 1 is a worksheet for the calculation of decompression schedules.

(1) The worksheet is described in Section 2.6.

(2) The symbols are defined in Article 2.2.20.

(3) The procedure for calculation is given in Part 3. When no other parameters are available, the following can be used:

(3.1) Insert 1.00 in box g.
(3.2) Insert 20, 40, 80 and 120 in boxes h.
(3.3) Insert 2.5, 2.3, 2.1 and 2.0 in the corresponding boxes r.

7.1.2 Figure 2 is a worksheet for the tabulation of decompression schedules. The procedure for tabulation is given in Section 4.1.

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 T, a tabulation of the time function against the time interval for various tissue half times.

		EXP.	ASC	1	2	3	4	5	6	7	8	9	10
	D												
g	A												
	N												
	t												

	u												
h	f												
	$E^{\pm}$												
	P												
r	$S^{\pm}$												
	Q												
	M												

	u												
h	f												
	$E^{\pm}$												
	P												
r	$S^{\pm}$												
	Q												
	M												

	u												
h	f												
	$E^{\pm}$												
	P												
r	$S^{\pm}$												
	Q												
	M												

FIGURE 1

	DIVE	ASCENT	DECOMPRESSION STOPS										TOTAL ASCENT	SURFACE INTERVAL
			100	90	80	70	60	50	40	30	20	10		
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														

FIGURE 2

Decompression Table

		EXP.	ASC	1	2	3	4	5	6	7	8	9	10
	D												
g	A												
	N												
	t												

	u												
h	f												
	$E^{\pm}$												
	P												
r	$S^{\pm}$												
	Q												
	M												

	u												
h	f												
	$E^{\pm}$												
	P												
r	$S^{\pm}$												
	Q												
	M												

	u												
h	f												
	$E^{\pm}$												
	P												
r	$S^{\pm}$												
	Q												
	M												

FIGURE 1

	DIVE	ASCENT	DECOMPRESSION STOPS										TOTAL ASCENT	SURFACE INTERVAL
			100	90	80	70	60	50	40	30	20	10		
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														
DEPTH (feet)														
TIME (min.)														
TISSUE (min.)														

FIGURE 2

Decompression Table