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Experimental Diving Unit

NGF, Washington 25, D.C.

U.S. NAVY EXPERIMENTAL DIVING UNIT
NGF, WASHINGTON 25, D. C.

RESEARCH REPORT 1-57

CALCULATION OF REPETITIVE DIVING DECOMPRESSION TABLES

PROJECT NS185-005 SUBTASK 5 TEST 3

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15 AUGUST 1956

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ABSTRACT

This report covers the procedure and parameters used by UNIVAC to calculate repetitive diving decompression tables. The tables themselves are not given because they have not been tested. The report concludes: (1) that table testing should be selective but extensive, (2) that the computer coding should be modified, and (3) that the depth ratio should be examined carefully. The report makes recommendations on: (1) table testing, (2) calculation of repetitive tables, and (3) modification of the present calculation procedure.

SUMMARY

PROBLEM

Calculate suitable tables for repetitive dives.

FINDINGS

(1) Tables for 10, 60, 180, and 720-minute surface intervals have been calculated.

(2) Suitability of these tables remains to be determined by test dives.

(3) Certain aspects of the calculation procedure need improvement.

RECOMMENDATIONS

(1) Test the 720-minute table.

(2) Modify the calculation procedures to make the table adequate.

(3) Find the satisfactory minimum number of repetitive tables.

(4) Request certain specific modifications to the calculation procedure (6.2.0 (4)).

ADMINISTRATIVE INFORMATION

Ref: (a) BuShips ltr A9 ser 588-2255 of 14 Sep '54.
(b) BuShips-EDU Monthly Conference 5 Oct '54
(c) Project 185-005/(5)/3 Outline #1 dtd 16 Dec '54
(d) EDU Research Report 4-56.
(e) BuShips (Codes 223&588) - EDU Conference 15 Mar '56.
(f) EDU Ltr Ale Ser 105 of 3 April 1956.
(g) DTMB ltr J22/UNIVAC/1 (820:FT:hps) dtd 14 Jun '56.
(h) Project 185-005/(5)/3 Outline #2 dtd 13 Jun '56

Reference (a) requested computer services for the calculation of repetitive diving decompression tables. Reference (b) formally established the project "to develop decompression tables and procedures that will be used for repetitive dives."

Reference (c) outlined computation work necessary to provide repetitive diving decompression tables. Reference (d) covered the actual procedure for the computations.

Reference (e) established that the necessary computation work was sufficiently extensive to warrant computer services. Reference (f) requested the Bureau of Ships to furnish computer services for this project. Reference (g) transmitted the first four sets of tables (10, 60, 180, and 720-minute surface intervals) calculated by UNIVAC for this project. Reference (e) outlines test dives on the 720-minute table.

LCDR J. V. DWYER was assigned as Project Engineer. Dr. Theilheimer and Mrs. Wiley (David Taylor Model Basin) were responsible for programming (coding) UNIVAC to produce the schedules, and for delivery of the first four tables (reference (d)).

The bulk of time and manpower involved in this report is properly chargeable to the Applied Mathematics Branch (Code 820) at David Taylor Model Basin. Experimental Diving Unit manpower requirements for this phase of the project were as follows:

DESCRIPTION	MANHOURS
Conferences	40
Reporting	84
Duplicating	6
TOTAL	130

Work commenced 23 April 1956 and completed 4 June 1956. The manuscript was submitted for review 16 August, and was approved 12 September 1956. This report is issued in the Research Report series, with unrestricted distribution. It is the second report for the project, and is an interim report.

CONTENTS

1. OBJECT

1.1 Introduction

Because of limitations in equipment and operational requirements in the past there was no significant need for decompression tables for repetitive dives. However, the advent of dependable scuba diving gear and changes in the operational requirements have established definite need for such decompression tables. With the present emphasis on scuba diving and anticipated future development of open-circuit scuba, repetitive dive decompression tables have become mandatory.

1.2 Objectives

The objective of this project is to devise safe decompression tables for divers who within a 12-hour period make two or more dives while breathing air in the depth range from 40 to 300 feet.

1.3 Scope

1.3.1 The scope of this project is

(1) To calculate suitable tables

(2) To prove those tables by test dives.

1.3.2 This report covers only the initial calculation of suitable tables.

2. DESCRIPTION

2.1 Background

2.1.1 Even after adequate decompression, an air diver surfaces from a single dive with a considerably greater amount of nitrogen partial pressure in his tissues than when he started the dive. While he remains at the surface he "desaturates", losing excess nitrogen until all his tissues equilibrate with nitrogen partial pressure at the surface. In theory, complete desaturation can require as long as 12 hours. If the diver makes another dive within 12 hours, he starts with more nitrogen partial pressure in his tissues than for the first dive. The net effect is a higher nitrogen partial pressure in at least some of his tissues after the second exposure, requiring more decompression than the U.S. Navy Standard Air Table would provide for the depth and time of the second dive.

2.1.2 The present Bureau of Ships Diving Manual (1952) (NavShips 250-880) recognizes the problem, and gives the following rule to provide adequate decompression for repetitive dives: "Use the combined times on bottom for all exposures and the depth of the latest dive in determining the decompression schedule to use." This rule is usually more than adequate, sometimes to the extent of placing prohibitive decompression requirements on the later dives. This is particularly true in self-contained diving with open-circuit equipment, where the air supply is severely limited. Yet the rule is theoretically unsafe for certain combinations of repetitive dives.

2.1.3 The Standard Air Table was formulated on principles established by Haldane and his associates[1]. These principles can easily be applied to calculate decompression for any sequence of dives. One procedure for calculation appears in Research Report 4-56.

2.1.4 Theoretically the amount of desaturation for a fully saturated tissue at the surface depends only on the time interval since surfacing. In normal calculations only one tissue surfaces fully saturated; the others are already below their maximum allowable tissue pressures.

2.1.5 The possible combinations of successive diving conditions is astronomical, making it impractical to have exact tables for all repetitive dives To keep the number of tables within practical limits it is desirable to assume that for the preceding dive all tissues surfaced fully saturated to their maximum allowable tissue pressures.

2.2 Approach

2.2.1 Research Report 4-56 furnishes satisfactory instructions for programming a computer. The logical approach seemed to be to request computation services from the Bureau of Ships digital computer.

2.2.2 The parameters for the computations were agreed on by the EDU staff in conference. These parameters were given to Dr. Theilheimer of the Applied Mathematics section at David Taylor Model Basin.

2.2.3 Mrs. Wiley of the Applied Mathematics section coded the program for the computer.

2.3 Tissue ratios

2.3.1 Boycott, Damant, and Haldane[1] provided a rational basis for calculation of decompression tables. Their theories have resulted in a general calculation procedure known as the "Haldane method" of calculating decompression schedules.

2.3.2 The critical parameter in the Haldane method is the numerical value of the "tissue ratio" (Research Report 4-56: 2.2.18). The original investigators derived a "total pressure" ratio of 2:1 and assumed no change with depth. Later investigators[2] felt that a ratio of 2:1 was too restrictive for fast tissues, and possibly not restrictive enough for very slow tissues. They ultimately developed the present U.S. Navy Standard Air Decompression Table using only three tissues with the following basic ratios:

20-minute tissue	2.8:1
40-minute tissue	2.0:1
75-minute tissue	2.0:1

The tissue ratios for the 5 and 10-minute tissues appeared to be so high that they did not normally bring those tissues into control.

2.3.3 Tests of schedules calculated by the three-tissue method indicated that the ratios had to be reduced after prolonged exposures at greater depths. The pattern of reduction used in the calculations was somewhat irregular, but the following values of tissue ratio were applied to fit empirical test results:

20-minute tissue	2.45:1
40-minute tissue	1.75:1
75-minute tissue	1.75:1

2.3.4 Van der Aue and his associates[3] analyzed available data to find logical values for tissue ratios. They then calculated and tested an extensive series of surface decompression schedules. They ultimately found: (1) that the fast tissues sometimes controlled deep stops, even with high tissue ratios, (2) that tissue ratios must be cut back considerably for all tissues in the longer, deeper dives, and (3) that the surfacing ratios could be increased to the following values:

5-minute tissue	3.80:1
10-minute tissue	3.40:1
20-minute tissue	2.80:1
40-minute tissue	2.27:1
75-minute tissue	2.06:1
120-minute tissue	2.00:1

2.3.5 Bateman[4] derives a mathematical relationship between "decompression ratio for symptom threshold" and "body saturation with air before decompression". Basically the relationship is a smooth reduction of tissue ratio with increasing tissue pressure, and is shown on a graph for a moderate (42-minute) "tissue" and very slow (208-minute) "tissue". (Bateman speaks of people rather than tissues.) The surfacing values appear to be very high when compared with Van der Aue's values:

42-minute tissue	4.00:1
207-minute tissue	2.85:1

2.3.6 Piccard[5] discusses the mathematical probability of a reduction in allowable supersaturation as the total mass of dissolved gas increases with increasing pressure.

2.3.7 Reduction of tissue ratio with depth appeared to be essential for calculating safe tables by the Haldane method. The surface ratios indicated by Van der Aue were selected as basic tissue ratios. The tissue ratio cutbacks used for the Standard Air Tables were used as a guide for mathematical cutback. The first attempt at "curve fitting" involved making the tissue ratio a direct function of final tissue pressure. This method appeared to cut back too fast and in the wrong ranges. The final method involved an empirical fit using a tenth-power relationship between tissue ratio and tissue pressure (3.2.2).

3. PROCEDURE

3.1 Method

3.1.1 The basic method for computation as given in Research Report 4-56 was used. The following steps were added.

(1) Tissue ratios were reduced in a mathematical relationship to increasing final tissue pressures on the bottom.

(2) The reduced tissue ratios were applied throughout decompression except for the last stop.

(3) Basic tissue ratios were used for the last stop.

3.1.2 The following parameters were set for the calculation of any dive.

(1) Six tissues: 5, 10, 20, 40, 80, and 120-minute half times.

(2) Saturation to total pressure, not to partial pressure (inert gas percentage decimal 1.00; tissue ratios adjusted accordingly).

(3) Six basic ratios ("surface" ratios): 4.0, 3.4, 2.8, 2.3, 2.1, and 2.0 respectively.

(4) At start of surface interval, each tissue saturated to maximum tissue pressure allowed by surfacing ratio.

(5) At end of surface interval, each tissue desaturated toward atmospheric pressure, exponentially by half time.

(6) Rate of ascent to first stop, 60 feet per minute.

(7) Instantaneous ascent between stops.

3.1.3 The following conditions were set for calculation of the tables.

(1) Calculate one complete table for each of the following surface intervals: 0, 10, 20, 30, 45, 60, 75, 90, 120, 150, 180, 240, 480, and 720 minutes.

(2) In each table, calculate schedules for 35 feet, and for 40 to 300 feet by tens.

(3) Calculate schedules at each depth for exposures from 0 to 30 minutes by fives, and from 40 minutes to the end point by tens.

(4) Use an exposure time end point (in minutes) of 12,000 divided by the depth in feet.

3.1.4 The following conditions were set for each schedule.

(1) Calculate tissue pressures throughout the dive, for all six tissues.

(2) Calculate ascent conditions to the nearest tenth of a minute.

(3) Calculate all stops to the next greater minute.

(4) Carry all tissue pressures to tenths of a foot.

(5) Use the depth ratios (3.2.1) throughout decompression except to surface from the 10-foot stop.

(6) Use the surfacing ratios to surface from the 10-foot stop.

3.1.5 For each schedule, the following data were presented on a single page:

(1) Depth (feet) - bottom and individual stops.

(2) Time (minutes) - bottom, ascent, and individual stops.

(3) Depth tissue ratios for each tissue.

(4) Final tissue pressures for every tissue at the end of bottom time, ascent, and each stop.

3.2 Tissue ratios

3.2.1 Tissue ratios were reduced mathematically to approximate empirical data (Section 2.3). The depth tissue ratio for each tissue was calculated as a function of the final tissue pressure at the end of bottom time. This ratio was applied throughout the decompression except for the last (the 10-foot) stop. For determination of time at this stop, the surfacing ratios were applied to all tissues.

3.2.2 The computer calculated depth tissue ratios to the nearest tenth. The following basic formulas applied.

$$r = s/J^{0.1}$$

$$\text{and} \quad J = (Q/33) - (r - 1)$$

where r = depth tissue ratio
s = surface tissue ratio
J = tissue pressure factor
Q = final tissue pressure at depth

3.2.3 The following surfacing tissue ratios were used (3.1.2 (3)):

(1) For the 5-minute tissue:	4.0
(2) For the 10-minute tissue:	3.4
(3) For the 20-minute tissue:	2.8
(4) For the 40-minute tissue:	2.3
(5) For the 80-minute tissue:	2.1
(6) For the 120-minute tissue:	2.0

4. RESULTS

4.1 Computed tables

4.1.1 Four tables have been received from the Applied Mathematics Branch at David Taylor Model Basin: 720, 180, 60, and 10-minute surface interval tables.

4.1.2 These tables are on hand at the Experimental Diving Unit. They will not be presented in this report, but will be the subject of a future report when the tables have been tested satisfactorily.

4.1.3 Figure 1 shows a single page from the computer calculations. This page is taken from the 60-minute (surface interval) table for the 230-foot, 40-minute schedule.

4.1.4 Figure 2 is a tabulation of the single-dive schedules for 200 and 210 feet presented as a sample. This tabulation is part of a summary presented in Project 185-006/(5)/3 Outline #2 for testing the repetitive tables.

4.2 Depth ratios

4.2.1 Figure 3 shows the mathematical curves for reduction of tissue ratio with increasing tissue pressure. In analyzing or using these curves, it is important to remember that the units of the coordinates are apparent rather than real.

(1) Tissue ratios are given as "absolute tissue pressure" to "absolute depth pressure" ratios. They are not true "partial pressure to absolute pressure" ratios.

(2) Final tissue pressures are given for equilibration to absolute depth pressure. They are not true partial pressure values.

4.2.2 These curves apply only to calculations for air decompression assuming the inert gas percentage decimal as unity (1.00). To apply these particular relationships to other nitrogen-oxygen mixtures, multiply both the ordinate and abscissa values by 0.79, and use the proper inert gas percentage decimal throughout the calculations.

5. DISCUSSION

5.1 Tables

5.1.1 There are ten tables still uncalculated. It may prove unnecessary to calculate all of these if the differences between tables are slight for a satisfactory sampling through the entire range of surface intervals out to 720 minutes (for example: 0, 15, 30, 60, 120, 240, 480, and 720 minutes; or 0, 10, 20, 45, 90, 180, 360, and 720 minutes).

5.1.2 Until the four available tables prove satisfactory there is no reason to calculate the remaining tables. Tests may show the need to alter some of the parameters and completely recalculate the entire set of tables. Certain changes should be made in any case (5.2.2).

5.1.3 The single-dive table (for a 720-minute surface interval) should receive extensive testing to determine the validity of the basic method of calculation. If this table proves satisfactory, tests of the repetitive tables will show the worth of assuming all tissues saturated to the surface ratios upon surfacing.

5.2 Programming

5.2.1 Certain inadequacies became apparent in the completed tables.

(1) Zero-decompression time should have been calculated to the nearest minute. At present it can be determined only to the next shorter 5-minute (or 10-minute) interval of bottom time.

(2) Calculations for 5-minute intervals of bottom time should have been made at least out to 60 minutes. The information is not needed for a practical diving table, but it is desirable for comparing the new single-dive table with the Standard Air Table. The standard table frequently gives schedules for bottom times which are odd multiples of 5 minutes, and does not give the adjacent even multiples of 5 minutes.

(3) The exposure time end point (3.1.3 (4)) should have had a value in minutes equal to 14,000 (rather than 12,000) divided by the depth in feet. Some of the schedules in the Standard Air Table extend beyond the end point used.

(4) Certain schedules should be available beyond the end point in any case to eliminate a separate "air saturation" table. Regardless of end point, schedules for the following bottom times are highly desirable: 60, 90, 180, 360, and 720 minutes.

5.2.3 Starting at the greatest exposure for a depth, and cutting back until zero decompression is determined can eliminate many unnecessary computations between zero-exposure time and zero-decompression time.

5.3 Depth ratios

5.3.1 In spite of the large cutback of tissue ratio with increasing tissue pressure (Figure 3), the depth tissue ratios may be too high to yield safe decompression schedules for the longer times at the greater depths. If this is the case, it will become necessary to derive empirical relationships to cut the tissue ratio back more rapidly with increasing tissue pressure, and yet not alter the cutback much for low tissue pressure. There are two simple mechanisms available to increase the cutback.

(1) Reducing the surface ratio itself.

(2) Decreasing the effect of the "J" factor by reducing the exponent (n) in the definition (from 3.2.2); or by recomputing the formula for the slope of the cutback.

$$J = (s/r)^n$$

5.3.2 Reducing the surface ratio itself simply moves the entire curve to the left (Figure 3), and slightly decreases the slope. For example, reducing the surface ratio from 2.3 to 2.1 would cause the curve for the 40-minute tissue to fall on the present curve for the 80-minute tissue. This action has the disadvantage of restricting the surface ratios, which have appeared reasonable from past experience.

5.3.3 Decreasing the effect of the "J" factor flattens the slope of the curve to the left without affecting the surface ratio. The broken line in Figure 3 shows the effect of changing the exponent for the 40-minute tissue from 10 to 8.

5.3.4 Logically, all of these curves should be asymptotic to a tissue ratio of 1.0, since such a value would not admit of any decompression without bubble formation. Meeting this consideration empirically would require an exponential relationship between tissue pressure and tissue ratio. From a practical aspect it is more desirable to adjust the present power relationship to fit test results. As a matter of interest, for the 10th power relationship, the present 120-minute curve reaches a tissue ratio of 1.0 when the tissue pressure becomes 33,792. For a 5th power relationship the 120-minute curve reaches 1.0 when the tissue pressure becomes 1056. Since air dives are confined to depths of 300 feet and less, the normal range of tissue pressure cannot exceed 333 feet in the method of calculation used here. Crossing an asymptote at 1056 feet is primarily a matter of academic interest if the depth tissue ratio is satisfactory at 333 feet.

5.3.5 These comments apply to empirical "curve fitting" for air decompression only. The same concepts may provide a starting point for a new attack on the problem of helium decompression, but the empirical curves may show quite a different shape and location.

5.3.6 One particular procedure in the calculations was followed to keep the computer time as short as possible: the depth ratio was applied to every phase of decompression except the last stop. (As the tissue pressure falls during decompression, the tissue ratio should increase toward the surface value. However recomputation of the ratio at each stop involved a considerable amount of machine time, and this procedure was discarded in favor of the "safer" procedure of applying the lowest tissue ratios throughout decompression.) In the case of very deep dives for extreme times (5.2.2 (4)), applying the depth ratio throughout decompression might produce unnecessarily extreme schedules.

5.4 Validity

5.4.1 Whether the new tables are valid can be shown only by a comprehensive series of test dives. If such a series developed no bends whatsoever, the tables could be suspected of excessive safety.

5.4.2 The major consideration is determination of the safety of the 720-minute surface interval table. Until this table is proven valid for single dives, tests of repetitive tables cannot be made. Bends caused by unsafe decompression from the first dive might receive partial treatment from the second dive, or might not produce symptoms until after the second dive.

5.4.3 A decompression schedule should be safe, but not prohibitively oversafe. On the other hand a safe schedule should not be reduced to an unsafe schedule merely to keep the total decompression time "within reason". If for some cause a diver has to spend an unusual amount of time at a great depth, the diving supervisor should have available a decompression schedule which will provide normal safety from decompression sickness if he uses it. The exigencies of the situation may force the diving supervisor to take other action, but he should be able to place as much trust in an emergency schedule as in any other. The schedules for "optimum" and "maximum" time given in the present Standard Air Table, and the schedules in the present Air Saturation Table, do not lend themselves to any such confidence.

5.4.4 The Haldane approach to adequate decompression provides a satisfactory starting point. The new tables are a step in the direction of increasing the trustworthy range of air decompression schedules. It may be necessary to modify them considerably in certain areas in order to make them completely satisfactory. All such modifications should aim at adequate but not excessive safety for the entire possible range of air diving, from the surface to 300 feet and from zero to infinite time.

5.4.5 Ultimately, only empirical results can prove the validity of any decompression table, and all adjustments to a table depend on those same results. The tests of these tables and any resultant modifications will become the subjects of future reports for this project.

6. CONCLUSIONS

6.1 Conclusions

(1) Table testing should proceed selectively, but extensively (Sections 5.1 and 5.4)

(2) Programming should be modified for further tables (Section 5.2).

(3) Choice of depth ratio cutback method should receive careful consideration (Section 5.3).

6.2 Recommendations

(1) Test the single-dive table first (5.1.3, 5.4.2).

(2) Modify the calculation procedure until the single-dive table is adequate (5.3.1, 5.4.4).

(3) Calculate a select group of tables for repetitive dive tests, and determine if these give a satisfactory minimum number of repetitive tables (5.1.1).

(4) Request at least the following modifications to the present procedure (5.2.2):

(a) Calculate zero-decompression time right to the minute.

(b) Calculate schedules at 5-minute intervals between 0 and 60 minutes of exposure time (except for zero decompression).

(c) Use an exposure time end point of 15,000 (minutes) divided by the depth in feet.

(d) Calculate schedules for 90, 180, 360, and 720-minute exposures at every depth, unless the exposure lies within zero-decompression time.

(e) Do not calculate schedules for exposures shorter than zero-decompression time (5.2.3).

7. FIGURES

7.1 Figures

(1) Figure 1 - Sample page as received from computer.

(2) Figure 2 - Summary tabulation for 200 and 210-foot dives after 720-minute surface interval.

(3) Figure 3 - Graph showing tissue ratio curves as a function of tissue pressure.

DECOMPRESSION SCHEDULE

UNIVAC PROBLEM 112

SURFACE INTERVAL 60 MINUTES

DEPTH TISSUE RATIOS 3.4 2.9 2.4 2.0 1.9 1.9

DEPTH	TIME	CONT. TISSUE	FINAL TISSUE PRESSURE					
230	49	-	262.1	248.7	207.4	155.6	115.5	98.9
ASCENT	2.8	20	239.8	236.1	204.6	156.7	117.0	100.2
60	3	20	200.5	217.4	197.1	154.5	116.6	100.1
50	8	40	121.8	160.3	169.5	145.2	114.3	99.3
40	18	40	77.0	98.1	124.7	125.9	108.3	96.7
30	22	40	63.7	77.6	91.8	106.0	100.4	92.7
20	58	80	53.0	53.3	59.2	72.4	81.7	81.4
10	89	120	43.0	43.0	43.7	49.3	60.9	66.0

FIGURE No. 1

SINGLE DIVE TABLE

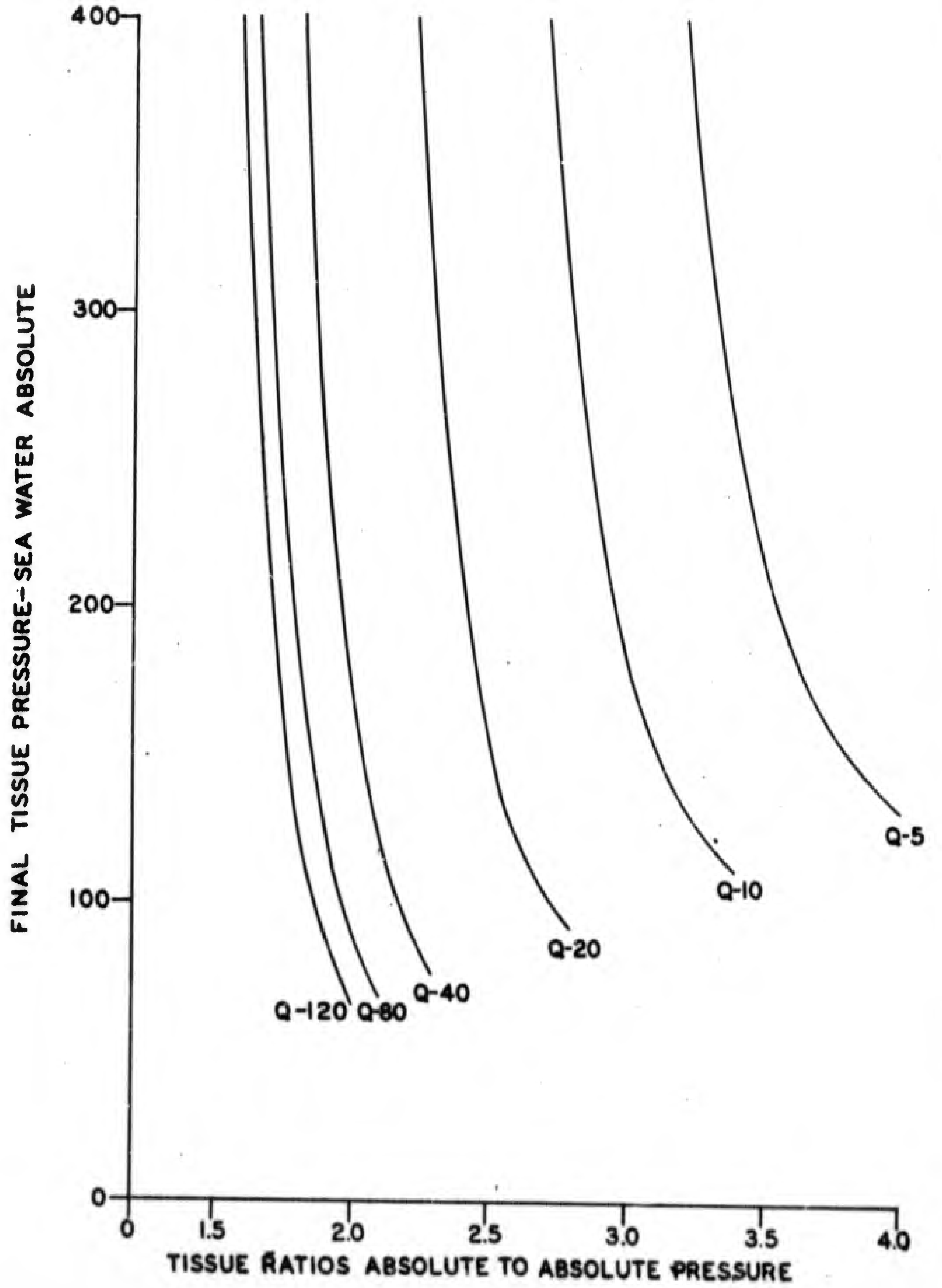
DEPTH 200

TIME OF DIVE	TO FIRST STOP	DECOMPRESSION STOPS								TOTAL
		80	70	60	50	40	30	20	10	
5	3.2								1	4.2
10	3.0							1	4	8.0
15	2.8						1	4	8	15.8
20	2.8						3	7	19	31.8
25	2.8						7	14	21	44.8
30	2.7					2	9	22	22	57.7
40	2.5				2	8	15	25	43	95.5
50	2.5				6	16	22	39	59	144.5
60	2.3			2	12	19	22	53	73	183.3

DEPTH 210

TIME OF DIVE	TO FIRST STOP	DECOMPRESSION STOPS								TOTAL
		80	70	60	50	40	30	20	10	
5	3.3								1	4.3
10	3.2							2	4	9.2
15	3.0						1	5	10	19.0
20	3.0						4	10	19	36.0
25	2.8					2	7	17	21	49.8
30	2.8					4	9	24	26	65.8
40	2.7				4	8	17	26	47	104.7
50	2.5			1	8	18	22	44	64	161.5

FIGURE 2



FINAL TISSUE PRESSURE - SEA WATER ABSOLUTE
400
300
200
100
0
Q-120
Q-80
Q-40
Q-20
Q-10
Q-5
0
1.5
2.0
2.5
3.0
3.5
4.0
TISSUE RATIOS ABSOLUTE TO ABSOLUTE PRESSURE

FIGURE No. 3

APPENDIX A

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