NASA CR-
144560

REPORT ON COMPUTATION OF REPETITIVE HYPERBARIC-HYPOBARIC DECOMPRESSION TABLES

(NASA-CR-144560) REPORT ON COMPUTATION OF REPETITIVE HYPERBARIC-HYPOBARIC DECOMPRESSION TABLES (Lecler (Michel), Inc., Harvey, La.) 34 p HC $4.00 CSCL 06S
N76-11714
Unclas
G3/52 01926

by

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This research was supported by NASA
Contract No. NAS 9-14352

May 15, 1975

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By: Peter O. Edel

ABSTRACT

Using a Wang Series 2000 computer, repetitive diving tables were developed through this program patterned after the U.S. Navy Repetitive Diving Tables in terms of application and format. The tables were constructed specifically for NASA's simulated weightlessness training program at the Marshall Space Flight Center in Huntsville, Alabama. The tables provide for 8 depth ranges covering depths from 7 to 47 FSW, with exposure times of 15 to 360 minutes.

These tables were based upon an 8 compartment model using tissue half-time values of 5 to 360 minutes and Workmanline M-values for control of the decompression obligation resulting from hyperbaric exposures. Supersaturation ratios of 1.55:1 to 2:1 were used for control of ascents to altitude following such repetitive dives. Adequacy of the method and the resultant tables were determined in light of past experience with decompression involving hyperbaric-hypobaric interfaces in human exposures. Using these criteria, the method showed conformity with empirically determined values. In areas where a discrepancy existed, the tables would err in the direction of safety.

Increased flexibility of repetitive diving tables was obtained through the development of surface interval decompression tables for use with oxygen breathing which may be used separately or in connection with the surface interval credit tables for air breathing medium. Additional tables were also provided for determining the surface interval required (using air and/or oxygen breathing mediums) prior to ascent to altitudes of 5,000 to 17,500 feet which may, if desired, be continued in flight.

INTRODUCTION

Astronauts from the Lyndon B. Johnson Spacecraft Center, Houston, are required to carry out their simulated weightlessness training in a tank filled with 40 FSW (feet fresh water) at the Marshall Space Flight Center in Huntsville, Alabama. Wearing standard astronaut space suits pressurized to 3.5 psi (pounds per square inch) above ambient pressure, they are so weighted as to be naturally buoyant. Following their hyperbaric exposure, the astronauts are required to fly back to Houston.

If one assumes that only two dives will be made per day, which may be repeated up to five successive days, with an altitude exposure following any dive in the series, the possible combination of depths, exposure times, surface intervals, and altitudes, are for all practical purposes infinite. Because combinations are unlimited, calculating individual tables to cover all possible combinations of depth, exposure times, surface intervals, and altitudes which could be expected to occur in the training program is impossible.

Present recommendations for decompression schedules and altitude exposures used in connection with the above program are generally based upon the maximum anticipated limits which would be safe for any possible pressure-time combinations within the prescribed limitations. However, in practice, the vast majority, if not all, of the exposures would be expected to fall within one or more of the limits, and restrictions extend far beyond the actual decompression requirements relating to the exposures. The use of repetitive diving tables, with provisions for hypobaric exposures, has been considered to be a practical solution to this problem. This research project will provide the mathematical basis for the construction of repetitive tables to meet the requirements of NASA's simulated weightlessness training program.

BACKGROUND

Prior to NASA's requirements for hyperbaric-hypobaric pressure profiles in connection with simulated weightlessness training for the Gemini and Apollo Flight programs, the only work involving decompression tables interfacing hyperbaric-hypobaric exposures resulted from studies of Edel et al., in which the surface intervals following no-decompression air dives made prior to altitude exposures at 8,000 feet (maximum cabin pressure altitude attained in commercial air line passenger operations) were empirically determined.[1] An analysis of the decompression problems of a hyperbaric-hypobaric interface, including calculated decompression schedules, which applied to the requirements of the simulated weightlessness training program at the

Marshall Spaceflight Center, was provided by Edel.[2] These tables provided for exposure times of 120 minutes at 47 FSW (feet sea water)--the equivalent pressure at a depth of 40 FSW with a suit pressure of 3.5 psi over ambient pressure--to be followed by a direct ascent to surface. The schedules provided for a series of 2 dives per day separated by a 3 hour surface interval. These dives could be repeated on successive days (with a 15 hour separation between dives on consecutive days) up to a maximum of 5 days. Further provisions were made for an altitude ascent following any hyperbaric exposure in the series, to a cabin pressure altitude of 10,000 feet after a prescribed surface interval during which the subject would breathe either air or oxygen.

Later work by Edel, which employed tests with human subjects to determine the probability of an attack of decompression sickness using the previous calculated schedules, validated the concepts presented in the earlier report.[3] As a result of these tests, the following surface intervals (shown in Table No. 1) were recommended prior to an altitude ascent, following one or more exposures to an equivalent pressure of 47 FSW for a maximum duration of 120 minutes per exposure. While these tables would permit altitude ascent following any of the exposures within the maximum assigned limits, obviously any reduction in the exposure depths and/or times would permit proportional reductions in the decompression requirements--i.e., the surface intervals--prior to flight. An attempt was made to apply the SPAR pneumatic analogue computer to these conditions in order to allow more realistic surface intervals and higher cabin altitudes in flight for cases in which the hyperbaric exposures were less than the maximum exposure limits in the tested hyperbaric schedules. This computer was tested by exposing the device to pressure profiles which had been previously man-tested and hence evaluated in terms of decompression risk. In one case, a human subject was decompressed in a repetitive dive profile in accordance with the computer's recommendations.[4] An evaluation of these results indicated that the computer was only partially successful in providing safe and adequate decompression from hyperbaric exposures in general.

TABLE 1

DIVING DAY	DIVE No. A	SURFACE INTERVAL BETWEEN DIVES (hours)		SURFACE INTERVAL PRIOR TO ASCENT TO ALTITUDE (hours)		MAXIMUM CABIN ALTITUDE
		Same Day	Different Days	On Air	On Oxygen	(feet)
1	1	-	-	1	-	10,000
1	2	3	-	5	-	10,000
1	2	3	-	-	2	10,000
2,3,4,5	1	3	16	3	-	10,000
2,3,4,5	2	3	16	5	-	10,000
2,3,4,5	2	3	16	-	2	10,000
2,3,4,5	2	3	16	3	2	12,000

In the above report, some alternate methods of handling this problem were considered. The most promising alternative involved the calculation of repetitive diving tables which could be expanded to include altitude ascents, a procedure similar in principal to such tables presently in use by the U.S. and British Navies.[5,6]

The practical impossibility of handling the decompression requirements by means of standard (non-repetitive) tables is apparent when one considers the possible number of combinations which are possible. Even if only 2 dives are made per day during a five day week, using five depth ranges, five exposure times, five surface intervals, and five cabin pressure altitudes, there are over 6,000 possible combinations of the above (2x5x5x5x5x5) = 6,250). Fortunately, however, exposures producing approximately similar tissue tensions within preassigned P_{N_2} ranges may be grouped together. Consider for example the group of single exposures shown in Table 2.

TABLE 2

Depth (FSW)	Time (min.)	(Tissue Compartment P_{N_2} Values) D	E	F	G	H
12	360	33.6	32.9	32.2	31.5	30.9
17	180	33.4	32.3	31.6	30.7	30.0
22	150	34.4	33.2	32.2	31.2	30.5
27	120	34.8	33.4	32.4	31.3	30.5
32	90	34.3	32.9	31.9	30.9	30.1
37	90	35.6	33.9	32.8	31.6	30.8
47	60	34.6	33.1	32.0	30.9	30.2
LOWEST VALUE		33.4	32.3	31.6	30.7	30.0
HIGHEST VALUE		35.6	33.9	32.8	31.6	30.9

Note that in compartments D, E, F, G, and H the resultant tissue tensions from the exposures are extremely similar in all cases. Hence, the exposures can be considered to be approximately equal to each other in terms of resulting tissue tensions, and they may be grouped together to form an equivalent dive classification. This dive group can then be handled in the same manner as an individual dive for the purposes of calculating the surface interval required prior to a second exposure or maximum altitude which would be safe for various surface intervals considered. The desired information can be presented in the form of tables which can indicate the procedures to be followed for any pressure-time relationship within the framework of predetermined exposure limits.

Although repetitive diving tables providing for various depth-time combinations will err (since any designated grouping system must use limits imposed by the most obligating exposure within that group), such tables are designed to err in the direction of safety. However, the surface interval, beyond that necessitated by the actual decompression obligation incurred in any given exposure, would most often be measured in minutes, rather than in hours, as it is under the present system used by NASA.

BASIC METHODS OF DERIVING DECOMPRESSION TABLES

Empirical Method

In its purest form, the empirical approach neither assumes nor requires a background of information beyond an understanding of the scientific method of investigation. The investigator is given or assumes specific pressure exposures. Humans or animals are exposed to the predetermined conditions and then are either returned to surface pressure or to some predetermined reduced pressure, following various regimes (in successive dives) until an optimum, or safe, schedule is developed. During this process, each successive schedule is evaluated in terms of the success or failure of the decompression procedure as evidenced by the subject's development of, or freedom from, symptoms of decompression sickness. Subsequent schedules using the same exposure will then be modivied in terms of previous results. If the initial schedule resulted in a 'clean dive' (asymptomic for the subject), additional exposures would be made with schedules intended to successively decrease safety, until a schedule resulted in symptoms for one or more subjects. If the initial test resulted in symptomatic response by the subjects, the reverse course would be pursued: additional exposures in successive dives would use schedules intended to increase decompression safety until asymptomic response resulted. The final result would be a decompression schedule which could accurately define the decompression obligation resulting from the exposure (or exposures) under consideration. The obvious drawbacks to this method are the high cost of developing such tables and the degree of hazard to human subjects. This method was used by individual divers in attempts to provide ascent schedules from deep or prolonged dives prior to the turn of the century, and such empirically derived tables are still in use in remote parts of the world today.

Mathematical Models

Since each attempt to develop a decompression schedule for an untested exposure condition is usually related to previous data from other exposure conditions, general theories may be formulated for decompression obligations from various recorded exposure conditions. Using such data, the investigator will try to develop a theory explaining the effects of pressure upon the human body, and the body's reaction to pressure changes which produce the observed results in empirical studies. Using the data and the theoretical assumption derived from it, the investigator will attempt to formulate a mathematical model which can demonstrate agreement with the previously obtained results. The methods can then be extrapolated to develop decompression schedules for previously untested conditions. The degree of success will depend upon the accuracy of the data serving as a basis for the model, the soundness of the theoretical assumptions used to develop the model, and the degree to which the exposure conditions serving as the data base can provide sufficient information for extrapolation.

This was the method used by Haldane in the development of the first reliable air decompression tables based upon his own empirical experiments with goats.[7] The application of such models in practice indicates that present data is insufficient to extrapolate for <u>all</u> the pressures, exposure times, environmental conditions, variations in individual subjects' response to decompression profiles, etc. which are required by the diving community.

However, a method's usefulness may be defined in terms of its scope of application, and usually within the general framework of the data used to develop such methods, the degree of success is generally satisfactory. When applied beyond the data limits, such tables can usually be relied upon to develop decompression schedules which will not be very far removed from the actual decompression requirements of such an exposure. If, in a given instance, tests of a table prove the decompression procedure to be unsatisfactory, the schedules may be modified and retested until an acceptable standard of safety is achieved. If, on the other hand, the tests validate the table, it may be accepted without further modification, and may be used to evaluate the method of calculating the schedules. However, in the latter case, it is important to consider that a satisfactory test may also be a failure of the method if it is overly conservative and requires more decompression time than actually needed to safely fulfill the decompression obligation. Since the data base is insufficient to derive a general decompression formula which can work under all conceivable conditions, a model which usually provides decompression scheudles which do not result in deocmpression sickness will most probably err in the direction of safety in the majority of depth and exposure times.

The reduced accuracy of such a method (as opposed to the empirical approach) is considered to be more than compensated for in the reduction of time and cost (as well as in terms of safety to test subjects).

This approach can be more widely applied in developing decompression schedules than other methods considered. Calculations may be made using a slide rule and may involve elaborate computer systems or any intermediate degree of sophistication. Choice of the actual mechanism to be used to implement the table development is basically determined by time and cost factors, since the relative accuracy of the method depends primarily upon the adequacy of the formula (or formulas) used rather than the inherent accuracy of the system used to execute the mathematical steps.

Dive Grouping Or Equivalent Exposure Method

The mathematical model method cannot be applied if a requirement exists for a repetitive series of exposures which cannot be applied in terms of a specific or limited sequence of pressure-time stages. Although the computer may take all possible combinations into account and provide a set of tables covering many thousands of combinations of pressures and times which could exist under predefined limits, the result would be a huge volume (or a library of huge volumes) of tables to be consulted for any given specific combination of dives and surface intervals between such dives. Obviously the bulk of material which would be required would make such tables too unwieldy to be practical.

Clearly a satisfactory solution to the problem of repetitive diving tables requires a further step in the generalization of the basic problem. One solution to the problem was developed by Des Grange[8] and adopted by the U.S. Navy to form the repetitive air decompression tables currently in use. A similar method for management of repetitive diving was developed by Crocker[6] for British Naval usage, and still another counterpart exists in France.[9] The basic method identifies all exposures which fall within predetermined nitrogen tissue tension limits as equivalent dives identified by a common symbol. The symbol identifying P_{N_2} values common to all dives within that category can then be used as an entity in subsequent mathematical operations. As in the case of a specific exposure which results in given P_{N_2} values in the various tissue compartments, the dive group (with its predetermined P_{N_2} values for the same compartments) can be utilized to determine the surface interval required prior to making a second dive and the influence of the residual nitrogen retained in the body at that time to subsequent exposures. In the process of grouping equivalent dives, the maximum possible number of such dive groups is defined and limited so that the number of possible combinations is no longer infinite but reduced to a figure which can easily be computed and presented in the form of tables. Each dive can then be identified by some symbol (such as a letter) which represents the P_{N_2} values of all dives within that group. The surface interval between dives can then be calculated to reflect the gradual reduction of P_{N_2} values with time as indicated by reductions in the order of the symbols (commonly in alphabetical order) used. In addition, each symbol is identified in terms of its value in time at a given depth, which can be subtracted from the required time at such a depth, to indicate repetitive exposure time for a given decompression obligation. Hence, the change in group designations occurring during a surface interval can be (and is in practice) equivalent to reductions in equivalent exposure time at the depths considered within the framework of the tables, providing the necessary information, when added to a subsequent exposure time, to determine the required decompression schedule.

To provide adequate safety under the least favorable circ. stances which might be anticipated, a dive group designation w: include the highest tissue tension values which could occur fr(any dive within that group. Most (and possibly all) exposures within a particular group will therefore result in lower tissue tensions and hence will actually require less decompression than specified for the given category which identifies the exposure in question. However, exposures contained in any given group designation would be selected to fall within a framework sufficiently restrictive, with rega.. to compartment tissue tension levels, to minimize the degree of inequity between tissue tension levels in the various compartments in any of the dive profiles included. The specified decompression obligation for the most obligating dive in such a group (which would govern decompression for all dives within that group) should not, therefore, result in significantly greater decompression time than would be required for the least obligating dive within that group. Although it is inevitable that some inequities will occur as a result of such grouping procedures, the disadvantages are more than compensated by the advantages: ease in handling repetitive dives, reduced cost of table development, and flexibility in operation.

PURPOSE

This research effort was conducted under NASA contract No. NAS 9-14352 to develop repetitive diving tables which would provide for altitude ascents following no-decompression dives in the 0-47 FSW range. The tables were to be constructed in units of depth, time, and altitude, applicable to the practical requirements of the simulated weightlessness training program conducted at the Marshall Spaceflight Center in Huntsville, Alabama. Further, the tables were to be presented in a format similar to that used in the U.S. Navy-Diving Manual (NAVSHIPS 0994-001-9010) covering repetitive air diving exposures. In addition, tables were required to provide for altitude ascents from any dive in a repetitive series and include provisions for use of oxygen breathing during surface intervals to accelerate denitrogenation of the tissues prior to a subsequent dive or ascent to altitude.

BASIC ASSUMPTIONS

Calculation of Nitrogen Uptake and Elimination in Bodily Tissues

Of the several inert gases contained in the earth's atmosphere, the only one of special significance in this study is nitrogen. The concentrations of oxygen, carbon dioxide, and the rare gases (Ar, Kr, Xe, Ne, etc.) as they are normally present in the earth's atmosphere, are not considered to play a significant role in these considerations.

Bodily tissues respond to increased or decreased nitrogen partial pressure in the breathing medium by taking up or eliminating the gas at a rate determined by the time constant of the tissue in question and the gradient formed between the nitrogen partial pressure in the tissues and that in the inspired breathing mixture. The ultimate nitrogen partial pressure that is reached after a specific time interval, following a change in the nitrogen partial pressure in the breathing medium, is expressed in the following equation, used to represent nitrogen uptake and elimination in the calculations made in connection with this program:

$$P_t = P_o \pm [(P_a - P_o)(1 - e^{-kt})]$$

P_t: The final nitrogen partial pressure in feet sea water absolute (FSWA) in the tissues after exposure for t minutes.

P_o: The original tissue partial pressure of nitrogen in FSWA before the exposure.

P_a: Partial pressure in FSWA in the breathing medium.

e: Base of natural logerithms.

t: Exposure time in minutes.

k: $\frac{0.693}{t\ 1/2}$ (tissue time constant)

0.693: Logarithm to the base e of 2.

The rate at which a tissue responds to a partial pressure gradient (P_a-P_o) is therefore determined by k, the tissue time constant. A tissue having a large k value will respond rapidly to a change in nitrogen partial pressure, whereas a tissue having a low k value will respond slowly. For sake of convenience however, the rate is more commonly indicated by referring to the tissue half-time--i.e., the time required for a tissue to respond to a change in the partial pressure gradient by saturating (or desaturating) to half the partial pressure gradient formed. A "fast" tissue would reach this value in several minutes, whereas a "slow" tissue may take several hours to achieve it.

Supersaturation Ratio

Supersaturation may be expressed as the ratio of the partial pressure of inert gas (in this case nitrogen) in the bodily tissues to that of ambient pressure. During decompression the concern is with a state wherein the ambient pressure has been reduced to such a degree that the nitrogen in the tissues is in excess of the normal pressure level of tissue saturation--that is to say, the tissues are in a state of supersaturation. Once supersaturation has occurred within a bodily tissue, this unstable condition will resolve itself in one of two ways: (1) the nitrogen will be eliminated at a rate determined by the gradient formed (P_a-P_o) and the tissue half-time; or (2) the supersaturated solution will break down into stable gas and liquid phases, thus forming gas bubbles in the tissues.

In the latter instance, bubbles may in time redissolve without producing symptoms noticeable to the subject. However, bubble growth may continue to the extent that, in the absence of proper treatment, permanent damage or even death can result. Any degree of bubble formation between these two extremes may also develop. With regard to repetitive diving profiles, bubble formation, even if asymptomatic, must be avoided, since the formation of intravascular bubbles can result in alterations of the perfusion rate in the affected area, which in turn reduces the rate of gas elimination for the area in question. Under these conditions, a subject would not eliminate as much gas during the surface interval as indicated by the calculations. The quantity of gas would exceed the predicted, and hence safe, values for the subject in subsequent hyperbaric or hypobaric exposures.

Since bubble formation and subsequent development is dependent upon the degree of nitrogen supersaturation in a specific half-time tissue, the probability of bubble development can be reduced by a reduction of the supersaturation ratio used to determine the permissible amount of pressure reduction following a hyperbaric exposure.

In applying the supersaturation ratios to the individual tissue compartment half-times, Hawkins, Shilling, and Hansen (1935) demonstrated that the ratios varied, increasing as the tissue half-time decreased.[10] The M-values (which may be divided by the pressure of the depth in feet sea water absolute at which they are applied to convert to a supersaturation ratio) used by Workman in the calculation of air (or nitrogen-oxygen) dives for the tissue half-time compartments from 5 to 240 minutes are shown in Table 3.[11]

TABLE 3

Tissue 1/2 Time	5	10	20	40	80	120	160	200	240
Surfacing M-value	104	88	72	56	54	52	51	51	50
Supersaturation ratio (at surface)	3.15:1	2.7:1	2.2:1	1.7:1	1.63:1	1.57:1	1.55:1	1.55:1	1.5:[illegible]

In decompression from dives in which the human body had been totally saturated with nitrogen, the slowest tissue compartment would limit ascent and 'control' the decompression. In ascent to surface pressure under these conditions, the maximum permissible M-value would be 50 FSW, which would result from an indefinite exposure at a depth of 30 FSW breathing air, and would be equal to a supersaturation ratio of 1.5:1.

METHOD

In this study the formula (previously discussed) $P_t = P_o \pm [(P_a - P_o)(1-e^{-kt})]$ was used to represent nitrogen uptake and elimination in computations made in connection with this program. For the purposes of this program a Haldane model[7] was used which incorporated the tissue 1/2 times used by Workman (5 to 240 minutes).[11] To this model were added half-time values of 300, 360, and 480 minutes, which have been found necessary to predict the decompression obligation resulting from exposures wherein the slowest bodily tissues controlled or limited decompression (Edel).[12,13] Hence the initial mathematical model was constructed with tissue half-time compartments of 5, 10, 20, 40, 80, 120, 160, 200, 240, 300, 360 and 480 minutes.

The initial model utilized supersaturation ratios similar to those which can be derived from Workman's M-values for determining exposure limits in hyperbaric pressure profiles. For altitude ascents, the model initially utilized a supersaturation ratio of 1.5:1 applied to all compartments.

There is still some question as to whether or not a supersaturation ratio of 1.5:1 would represent a safe surfacing value applied to the slowest bodily tissue half-time compartment (assumed to be about 480 to 500 minutes based upon exposure involving total saturation with N_2-O_2 breathing mixture) (Markham and Edel,[14] Edel[12]). This value has been shown to be safe for exposures to altitudes of 25,000 to 35,000 feet (Edel).[15] In calculation for human exposures to the above altitudes, this ratio was applied to a tissue half-time of 360 minutes. Prior to the hypobaric exposures, nitrogen elimination was accomplished by preoxygenation at surface pressure in subjects whose P_{N_2} in all bodily tissue compartments was initially at equilibrium with the nitrogen partial pressure in the air at sea-level pressure. Obviously under such conditions, the tissue tensions of any half-time compartments slower than 360 minutes would have higher supersaturation ratios upon reaching altitude than the 360 minute half-time compartment. It was therefore assumed that a supersaturation ratio of 1.5:1 could be safely applied to the slowest bodily tissue half-time compartment as long as this ratio was used in connection with hypobaric pressure profiles.

It was realized, in the development of the mathematical model, that application would involve a maximum depth of 47 FSW, which in terms of absolute pressure would be 80 FSWA (47 FSW + 33 FSWA--sea level pressure--80 FSWA). With air (considered to contain 79.1% nitrogen) as the breathing mixture, nitrogen partial pressure at maximum depth (47 FSW) is 63.28 FSWA (80 FSWA x .791 = 63.28 FSWA). A glance at Table 3 shows that tissue half-times in excess of 40 minutes can tolerate surfacing levels well in excess of the maximum attainable pressure considered in this program. Hence tissue half-time compartments faster than 40 minutes were not included in the initial mathematical model nor in any subsequent variations.

In the construction of repetitive diving tables, one of the critical decisions is the proper assignment of the P_{N_2} values to be included in each group. Obviously, any attempt to provide for all possible combinations of all compartment P_{N_2} values would result in a number of group designations approaching the number of depth-time combinations considered. Attempts to simplify may prove unrealistic if inappropriate criteria are used in the selection.

Finally, one must provide for the worst possible case, or the system will fail to insure freedom from decompression sickness under some conditions. The method used by Des Granges, employing groups in which each successive group letter designation represents an increase in the tissue tension of the slowest tissue compartment of 2 FSW, has demonstrated its usefulness in practical application by the U.S. Navy.[8] However, for purposes of utilizing dive grouping methods for NASA's programs, the Navy system does not fulfill all requirements. In the Navy system the slowest tissue half-time considered was 120 minutes. Considering the scope of diving profiles to which this method was applied, it would appear to be adequate for the intended purpose, at least for the vast majority of conditions intended to be provided for by the system, since the slower tissue half-times would rarely, in practice, be expected to limit the exposures. In the case of NASA requirements however, the tables must cover altitude exposures in which, at least in some cases, the slowest bodily tissue compartment would control, or limit, decompression. Hence the system must provide for such events.

While faster tissue compartments do not become limiting in many repetitive exposures and altitude ascents during which a fairly long period of time is spent at surface pressure between exposures, this may not be true when fairly short surface intervals are required. An immediate ascent to surface following a 120 minute exposure to 47 FSW results in high tissue tensions in the faster half-time compartments which a. at that time, limiting and controlling decompression.

Under the. conditions, the slowest tissue compartment have much lower P_{N_2} value. in relation to their safe surfacing limits and would, at that time, permit altitude ascent. Therefore, if following such a dive, a very short surface interval were used prior to a hypobaric exposure, determination of the permissible altitude, based solely upon the nitrogen tissue tensions in the slower tissue compartments, would result in a pressure reduction unsafe for the faster compartments and which would be expected to provoke an attack of decompression sickness.

The model used for grouping of tissue tensions must then provide for all tissue compartments which could be affected in any repetitive diving or altitude ascent possible under all conditions considered. The most practical approach to this problem would be to apply a computer to possible attainable depth-time combinations which could exist within the framework of NASA requirements and develop groups to include all tissue compartments which might, under any foreseeable circumstance, limit or control decompression. Since the range of possible slowest tissue compartment P_{N_2} values in no-decompression dives to 47 FSW with a 3 hour exposure limit would be much less than the range which would occur in civilian or military diving practice, as provided for in the U.S. Navy Repetitive Diving Tables, it might be possible to utilize 1 FSW increment in the slowest tissue compartments, as opposed to the 2 FSW used by Des Granges.[8] This method would provide finer increments between group letter designations, resulting in potential savings in decompression requirements.

DEVELOPMENT OF NASA DIVE GROUP DESIGNATIONS

Depth was divided into 8 ranges in 5 FSW increments as follows: 7-12, 12-17, 17-22, 22-27, 27-32, 32-37, 37-42, 42-47. Eight exposure times were provided for as follows: 15, 30, 45, 60, 90, 120, 150, and 180 minutes. This allocation results in 8^2 or 64 possible depth-time combinations. Each of the above depth-time combinations (except for the two longest exposures at 47 FSW, which would not result in no-decompression dives) were then paired with a dive in each depth range for the longest exposure time achievable as a no-decompression dive in a given day, for a total of 8^3 (or 512) possible combinations. In each case, the profiles were repeated on a successive day, which totaled approximately 2000 individual dives to be analyzed by the computer.

In addition, some longer exposures were added in depths where repetitive exposures of 6 hours duration each could be safely tolerated. Such exposures were repeated again following a 15 hour surface interval. Dives on successive days after the second day were not considered, as a previous analysis had shown that the decompression obligation (under these conditions) did not increase after the second day (Edel).[2]

The dive profiles were written in the form of data statements which were fed into a Wang 2000 series computer (with a 8k memory unit) programmed to compute the tissue tensions in all compartments resulting from each pressure change. The compartment tissue tensions, depth, exposure time, repetitive dive number (and other information required for identification and retrieval purposes) were then saved on tape cassetts for retrieval at a later date.

In a separate program, the compartment tissue tensions were retrieved and the information was used to develop repetitive dive groups in accordance with pre-programmed criteria. The program analyzed the data from each dive and stored the tissue tension data from each compartment into one of 11 to 17 groups in which each successive group (identifiable as successive letters of the alphabet) had a P_{N_2} value in the slowest tissue half-time compartment of either 1 or 2 FSW higher than the preceding group.

If the data from a given dive included a P_{N_2} value of 35.5 FSWA in the slowest tissue compartment, the program would analyze in a subroutine the data derived from the slowest tissue half-time values ranging from 35 to 36 FSW. Within this subroutine, each compartment was analyzed to determine whether or not the compartment values exceeded values previously stored from earlier date in the memory for that compartment (for that particular group). Any value exceeding previously stored P_{N_2} values would be stored in the memory for its compartment number and group designation, leaving values stored in other compartments (and other group divisions) unchanged. Any value with a P_{N_2} value lower than that previously stored in a given compartment (for that particular group) was ignored. Once all dive data statements were processed, each program sub-division (repetitive dive group) contained the maximum P_{N_2} values in each compartment which could occur as a result of the dive profiles analyzed. Each group would therefore provide for the worst case (in terms of decompression obligation) which would result in a dive assigned to its category.

On completion of this task, the computer provided a hard-copy printout of these values, which were then manually adjusted upwards to provide integer values (where such values could logically be assigned) for the next stage of operations.

By comparing the results of grouping in successive increments of 1 FSW and 2 FSW in the slowest tissue compartments, it was concluded that 1 FSW increment used for the purposes of this program would require 16 group letter designations ("A" to "P"). This grouping would result in the reduction of surface interval requirements prior to a succeeding hyperbaric or hypobaric exposure and/or increased exposure time in succeeding dives. Accordingly, no further consideration was given to use of grouping methods using 2 FSW increments.

Using the assigned P_{N_2} values for each letter group, each of the previously mentioned initial depth-time combinations (eight times for each of eight depths) was assigned a group letter. Each of the depth-time combinations in turn was computed to determine the tissue tensions in each compartment resulting from the exposure. The computer analyzed these values to determine which was the lowest group which could accommodate the P_{N_2} values without exceeding the preassigned limits for that group and then provided a hard copy of each depth-time combination with an assigned group letter. This analysis was based on both 360 and 480 minute tissue half-times for the slowest tissue compartments.

The final group letter designations for the depth-time combinations shown in Table 4 reflect a 360 minute half-time value for the slowest tissue compartment.

TABLE 4

REPETITIVE GROUP DESIGNATION TABLE

DEPTH	TIME	GROUP	DEPTH	TIME	GROUP
12	15	A	32	15	A
12	30	A	32	30	B
12	45	A	32	45	C
12	60	B	32	60	C
12	90	B	32	90	E
12	120	C	32	120	F
12	150	C	32	150	G
12	180	C	32	180	H
12	240	D	32	240	J
12	300	E	32	300	L
12	360	E	32	360	M
17	15	A	37	15	A
17	30	A	37	30	B
17	45	B	37	45	C
17	60	B	37	60	D
17	90	C	37	90	E
17	120	C	37	120	G
17	150	D	37	150	H
17	180	E	37	180	I
17	240	F	37	240	K
17	300	G	37	300	O
17	360	G			
22	15	A	42	13	B
22	30	B	42	30	B
22	45	B	42	45	C
22	60	C	42	60	D
22	90	C	42	90	G
22	120	D	42	120	G
22	150	E	42	150	I
22	180	F	42	180	J
22	240	G			
22	300	H			
22	360	I			
27	15	A	47	15	B
27	30	B	47	30	C
27	45	B	47	45	D
27	60	C	47	60	E
27	90	D	47	90	G
27	120	E	47	120	H
27	150	F			
27	180	G			
27	240	I			
27	300	J			
27	360	K			

RESIDUAL NITROGEN TABLE DEVELOPMENT

In the following program, all groups were examined by the computer to determine the length of time required for each group to effect successive reductions in group letter designations with air or oxygen as the breathing mixtures during the surface interval. In each case, the previously selected P_{N_2} values for the group in question were fed into the computer as initial values. The standard gas exchange formula was then applied to these values to compute tissue tension reductions occurring at pre-selected time intervals during a period of residence at surface pressure. Following the computations made at each of the programmed time intervals, the new P_{N_2} compartment values were compared with the assigned values for each of the letter groups, and a group letter designation was applied to represent the group having the lowest P_{N_2} value limits in which any compartment did not exceed the designated P_{N_2} limit for that group. The resulting printouts which showed the reduction of group letter designations with time at surface pressure served as the basis for the surface interval credit tables for air and oxygen (in which oxygen was considered to be 80% effective) shown on pages 17 and 18 (Tables 5 and 6).

Since only after an infinite period of time breathing air at surface pressure would the expression e^{-kt} mathematically result in equilibrium of the P_{N_2} values in the tissue compartments with the P_{N_2} of the breathing medium, computations would never normally indicate a return to the P_{N_2} of air at sea-level pressure in an unmodified program. The computer was therefore instructed to regard a P_{N_2} value of 26.3 FSWA in any compartment as being in equilibrium with the P_{N_2} value of air at sea-level pressure (26.1 FSWA). Hence, once all compartments achieved a value equal to or less than 26.3 FSWA, the condition was no longer considered to be within the framework of a repetitive exposure. It should be noted that the time required for denitrogenation to permit a reduction from a given letter to the next lowest letter is usually less if that letter does not represent the initial condition in this table. This is due to the influence of tissue compartments with half-times faster than the slowest. In the initial P_{N_2} values of a group letter designation, higher tissue tensions exist in the faster tissue compartments as compared with the slowest compartments. A portion of the time required to denitrogenate sufficiently to allow for a reduction of the initial group letter designation to the next lowest group letter may be due to the time required for nitrogen loss in the compartment other than the slowest. If this denitrogenation process had continued sufficiently to result in the slowest compartment having the highest tissue tension values, the time required for this group letter change would be less. Hence, if a pressure exposure results in a specific group letter designation such as "J," <u>only</u> the J column should be used to indicate the surface interval by the reduction of group letter designation (as opposed to using the "J" column to indicate the time required to reduce the group letter designation to "I" and then using the "I" column to indicate the time required to reduce the group letter designation to the next letter, etc.). While it is doubtful that such a practice would

TABLE 5

GROUP DECAY FOR MAXIMUM 1/2 TIME TISSUE OF 360 MINUTES SURFACE INTERVAL
CREDIT TABLE FOR SUBJECT BREATHING AIR
(in Hours and Minutes)

P	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A	Clear
0:45	O															
1:20	0:45	N														
2	1:20	0:45	M													
3	2	1:40	0:45	L												
3:30	3	2:30	1:40	1	K											
5	4	3	2:30	1:40	1	J										
6	5	4	3:30	3	2	1	I									
7	6	5	5	4	3	2	1:20	H								
8	7	7	6	5	4	3:30	2:30	1:20	G							
10	9	8	7	7	6	5	4	3	2	F						
12	10	10	10	8	7	7	6	5	3	1:40	E					
14	12	12	12	10	10	10	8	7	5	4	2	D				
16	16	14	14	14	12	12	10	10	8	7	5	3	C			
20	20	20	20	16	16	16	14	14	12	10	10	7	4	B		
32	32	24	24	24	24	24	20	20	20	20	16	14	12	7	A	
40	40	40	40	40	40	40	40	32	32	32	32	32	24	20	14	clear

TABLE 6

SURFACE INTERVAL CREDIT TABLE FOR SUBJECT BREATHING OXYGEN
(Time in Minutes)

P	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A	Clear
15	0															
35	20	N														
50	35	20	M													
70	50	35	20	L												
80	70	50	35	20	K											
100	90	70	55	35	20	J										
120	100	90	70	55	40	20	I									
135	120	110	90	80	55	40	20	H								
165	150	135	110	100	80	60	40	25	G							
180	165	150	135	120	100	80	70	50	35	F						
200	180	165	150	135	120	100	80	70	50	25	E					
220	220	200	180	165	150	120	110	90	70	45	25	D				
240	240	220	200	180	165	150	135	110	90	70	45	25	C			
270	270	240	220	200	200	165	150	135	120	90	70	50	30	B		
300	285	270	255	240	220	200	180	165	150	120	100	80	60	35	A	
330	300	300	270	270	240	220	200	180	165	135	120	90	70	45	20	clear

normally be attempted while only one breathing medium is to be used during a surface interval, some confusion might exist in transferring from the air to the oxygen credit tables or vice versa. For optimum results, in all cases the column representing the group letter resulting from the initial or cumulative exposures on arrival at surface pressure is to be followed until the surface interval is completed or the table indicates no further repetitive group letter designations.

The surface interval credit tables allow for use of air or oxygen breathing, either separately or interchangeably. In the latter case some consideration should be given to the practicality of switching from air to oxygen or vice versa, as opposed to remaining on either breathing mixture alone. If a specific surface interval breathing air will satisfactorily reduce a group letter designation prior to subsequent exposure or flight within a reasonable time, it would appear to be unwarranted to use oxygen for the purpose of denitrogenation. If oxygen is desired, the discomfort of using the mask, the limitations to mobility, and other considerations may restrict the use of this breathing medium to some degree.

Obviously if the tissue tensions are sufficiently elevated, some oxygen may be required, and some judgment is necessary to obtain optimum use of the breathing mixture within reasonable restrictions as to its use. When air and oxygen are both to be used as breathing mediums, optimum results are obtained when air is used as the breathing medium during the initial portion of the surface interval, and oxygen during the final portion. On arrival at surface (following a hyperbaric exposure) the P_{N_2} gradient (the difference between the P_{N_2} in the tissue compartments and the P_{N_2} in the inspired breathing medium) is the greatest; hence the amount of nitrogen removed from the tissues is the greatest per unit time. As the tissues lose nitrogen, the gradient is diminished, and the amount of nitrogen removed per unit time from the tissues decreases. Hence the greatest benefit, with respect to nitrogen elimination, occurs in the initial portion of the surface interval, and it is recommended that air be used as the breathing mixture at that time.

As the gradient decreases, the ratio of P_{N_2} elimination for oxygen increases as opposed to nitrogen. Since maximum benefits for nitrogen elimination from oxygen breathing increase as time at surface pressure continues, the use of oxygen is recommended during the latter portion of the surface interval.

REPETITIVE DIVE DEPTH TABLE

The repetitive dive depth table was in essence derived from the initial grouping procedure without significant modification, except for the addition of longer exposure times necessary to allow for depth conversion. As can be seen from Table 7, all the dives shown fall within the same group letter designation and hence are truly equivalent to each other for the stated purposes of this table.

TABLE 7

[TISSUE COMPARTMENT HALF-TIME]

Depth	Time	40	80	120	160	200	240	300	360
12	360	35.6	35.2	34.4	33.6	32.9	32.2	31.5	30.9
17	180	39.0	36.7	34.8	33.4	32.3	31.6	30.7	30.0
22	150	42.2	38.9	36.2	34.4	33.2	32.2	31.2	30.5
27	120	44.8	39.9	36.8	34.8	33.4	32.4	31.3	30.5
32	90	46.1	39.8	36.4	34.3	32.9	31.9	30.9	30.1
37	90	49.2	42.0	38.0	35.6	33.0	32.8	31.6	30.8
47	60	50.1	41.2	37.0	34.6	33.1	32.0	30.9	30.2
LOWEST VALUE		35.6	35.2	34.4	33.4	32.3	31.6	30.7	30.0
HIGHEST VALUE		50.1	42.0	38.0	35.6	33.4	32.8	31.6	30.9
DIFFERENCE		14.5	6.8	3.6	2.2	1.6	1.2	.9	.9

All dives shown are 'E' dives, and since calculations are based upon the highest possible values which can occur, all are accommodated by the same denitrogenation procedures. The relationship is a simple one since we are dealing with no-decompression dives in which the tissue tension values resulting from the hyperbaric exposures are not altered by a significant period of decompression to sea level.

The equivalent dive table (Table No. 8) may be used to determine the residual time for a given depth following the surface interval after a dive, or the equivalent exposure in changing from one depth to another, in the same manner as Tables 1-11 or 1-13 in the U.S. Navy diving manual. If a diver were at 27 FSW for 90 minutes and

TABLE 8

EQUIVALENT TIME FOR GROUP LETTER VALUES

Depth	A	B	C	D	E	F	G	H	I	J	K	L	M	M	O	P
12	45	90	180	240	360	480	560	720	960	1440						
17	30	60	120	150	180	240	360	420	480	600	720	960	1200	1440		
22	15	45	90	120	150	180	240	300	360	420	480	560	600	720	840	1200
27	15	45	60	90	120	150	180	210	240	300	360	420	480	520	560	660
32	15	30	60	75	90	120	150	180	210	240	270	300	360	390	420	480
37	15	30	45	60	90	105	120	150	180	210	240	260	280	290	300	310
42	10	30	45	60	70	80	120	135	150	180						
47	5	15	30	45	60	75	90	120								

needed to work at the 12 FSW level, Table 8 (or Table 4) would show that his group letter for that exposure is 'D'. Table 8 further shows that the equivalent time for that group at 12 FSW is 240 minutes. If he then worked for one hour at 12 FSW, his total time (exposure time at 12 FSW + the equivalent exposure of 240 minutes resulting from the time spent at 27 FSW = 300 minutes) would be 5 hours, and would place him in group E. He could then surface as an 'E' group diver or return to any depth shown with the residual time indicated by the table added to any further exposure at said depths.

ALTITUDE EXPOSURE TABLES

The altitude exposure tables (Tables 9 and 10) were derived from essentially the same process as the surface interval credit tables (Tables 5 and 6). The assigned P_{N_2} values for each group letter designation were used as the initial values at the start of the surface interval. The computer determined the decrease in these values for pre-selected increments of time (for both air and oxygen breathing mediums) and compared the values with safe super-saturation ratios to indicate the maximum altitudes which could be safely attained.

A safe altitude was determined by the ratio of compartment P_{N_2} cabin pressure altitude in FSW. The governing ratios were extrapolated from altitude data on file from previous programs. Use of these tables is essentially the same as for the surface interval credit tables, and the same basic considerations apply in both cases. Optimization requires using only the column relating to the terminal group letter which applies from the last hyperbaric exposures until such time as the table is no longer in effect (bodily tissue P_{N_2} values in equilibrium with the P_{N_2} of the air at sea-level pressure), or until the flight has been completed. Maximum benefits also occur when air is used during the initial portion and oxygen is used during the latter portion of the surface interval, for the same reasons stated in connection with the surface interval credit tables. These tables can be continued during the flight if desired, while altitude may be increased, according to the table, with the passage of time if such practice is permissible and advantageous.

RESULTS

The use of a 9 compartment model with a slowest tissue half-time at 480 minutes did not produce tables which compared with empirically derived data, which were predictive of the decompression obligation incurred in repetitive hyperbaric exposures nor in surface intervals required prior to altitude ascents. In both instances the decompression obligation, as indicated by the computer's predictions, were much greater than has been shown by manned experience. This result indicates the following:

TABLE 9

AIR

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	ALTITUDE
0:00	0:00	0:00	0:00	0:00	0:00	0:15	0:15	0:15	0:30	0:30	0:30	0:45	1:00	1:20	1:20	5,000
0:00	0:00	0:00	0:00	0:10	0:15	0:30	0:45	1:20	1:40	2:00	2:00	2:30	2:30	3:00	3:00	8,000
0:00	0:00	0:00	0:15	0:15	0:30	1:20	2:00	2:00	3:00	3:00	4:00	4:00	5:00	5:00	5:00	10,000
0:00	0:00	0:15	0:30	1:20	1:40	3:00	4:00	5:00	5:00	6:00	6:00	7:00	7:00	8:00	9:00	12,000
0:00	0:00	0:45	1:40	2:30	3:00	5:00	5:00	6:00	7:00	7:00	8:00	8:00	8:00	10:00	10:00	13,000
0:00	0:15	2:00	3:00	4:00	5:00	6:00	7:00	8:00	8:00	9:00	10:00	11:00	11:00	12:00	14:00	14,000
0:15	1:40	4:00	5:00	6:00	7:00	9:00	10:00	11:00	12:00	12:00	14:00	14:00	14:00	16:00	16:00	15,000
1:40	7:00	10:00	12:00	14:00	16:00	18:00	18:00	20:00	20:00	23:00	23:00	23:00	23:00	23:00	26:00	16,500
14:00	20:00	24:00	32:00	32:00	32:00	32:00	32:00	40:00	40:00	40:00	40:00	40:00	40:00	40:00	40:00	17,500

TABLE 10

OXYGEN

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	ALTITUDE
0:00	0:00	0:00	0:00	0:00	0:00	0:05	0:10	0:10	0:10	0:15	0:15	0:25	0:30	0:40	0:40	5,000
0:00	0:00	0:00	0:00	0:05	0:10	0:15	0:25	0:30	0:45	0:50	1:00	1:10	1:10	1:30	1:30	8,000
0:00	0:00	0:00	0:05	0:10	0:15	0:35	0:45	1:00	1:10	1:20	1:30	1:40	1:50	2:00	2:15	10,000
0:00	0:00	0:10	0:10	0:25	0:35	1:10	1:20	1:40	1:50	1:50	2:15	2:30	2:45	2:45	3:20	12,000
0:00	0:00	0:10	0:25	0:40	0:50	1:20	1:40	1:50	2:00	2:15	2:30	2:45	3:00	3:20	3:40	13,000
0:00	0:05	0:30	0:40	0:55	1:10	1:40	2:00	2:15	2:30	2:45	3:00	3:20	3:40	4:00	4:30	14,000
0:00	0:20	0:45	1:00	1:10	1:30	2:15	2:30	3:00	3:00	3:20	3:40	4:00	4:00	4:30	5:00	15,000
0:10	0:45	1:20	1:30	1:50	2:15	2:45	3:00	3:20	3:40	4:00	4:30	5:00	5:00	5:30	5:30	16,500
0:30	1:00	1:45	2:00	2:00	2:30	3:15	3:30	4:00	4:00	4:30	5:45	6:00	6:00	6:30	6:30	17,500

A: Use of the 480 minute half-time compartment resulted in much longer denitrogenation period than actually required prior to altitude ascents or repetitive hyperbaric exposures.

B. The use of a 1.5:1 ratio did not permit altitudes to be achieved which manned experience has previously shown to be safe with respect to decompression sickness.

Accordingly, the ratio was increased to 1.55:1, and the final compartment (with a half-time of 480 minutes) was deleted, leaving the 360 minute half-time value for the slowest tissue compartment. This value had been previously used with success in predicting surface intervals prior to altitude ascents following hyperbaric exposures in other NASA studies (Edel).[5]

The use of this model was most successful in predicting decompression requirements in repetitive dive profiles in which the computer was programmed to indicate changes in group letter designation using dive profiles which had previously been man-tested. However, use of this model was less successful under some conditions in providing for adequate surface intervals prior to an altitude ascent. It appeared that the surface intervals using oxygen were less than adequate for altitude ascents following prolonged hyperbaric exposures and that the indicated time for surface intervals following shorter exposures (such as a single dive to 47 FSW for 120 minutes) was significantly longer than had been shown to be necessary in manned tests.

Analysis showed the cause of these inconsistencies to be the supersaturation ratios used to control altitude ascents for the faster tissue half-time compartments. The use of a ratio of 1.55:1 for these compartments limited ascents in the initial portions of the surface interval while these compartments were controlling pressure reductions. The ratios for those compartments were accordingly increased to values formerly used. It was reasoned that the use of 20% N_2 value for oxygen breathing was insufficient for the longer surface oxygen exposures, and the differences between the mathematical prediction and empirical results could be ascribed to the effects of vasoconstriction. This value was accordingly increased to 30% to provide for a more realistic assessment of this influence on the slower tissue compartments. The final supersaturation ratios used for the various half-time compartments are shown in Table 11.

TABLE 11

Compartment 1/2 Time Value	40	80	120	160	200	240	300	360
Compartment Ratios	2:1	1.8:1	1.7:1	1.6:1	1.55:1	1.55:1	1.55:1	1.55:1

An analysis was made of the system by generating specific profiles (previously used in tests with human subjects) in which the computer was programmed to provide a group letter printout at each pressure change. When analyzed in terms of previous manned experiments testing hyperbaric-hypobaric shcedules, these tables indicated, in most cases, very close agreement with empirically derived results. In cases where disagreement occurred, the error was always in the direction of safety.

The test provided information for the mathematical model used to derive the system. In operation, some inequities must occur to permit the operation of the general method to cover all conceivable depth-time-surface-interval-altitude combinations which could result within the framework of NASA requirements. Such inequities will result from the fact that each group consists of eight compartment limiting values. To fall within a group, an exposure need only result in one compartment with sufficiently high P_{N_2} values to be classified within that group, while remaining compartments may have tissue tensions far below the levels set for the group in question. Denitrogenation in these tables is based upon the assigned values for specific group letter designations. Therefore the denitrogenation after a specific hyperbaric exposure (with only one compartment sufficiently elevated to fall within that group) may occur more rapidly than indicated by the tables (in which all compartment values must be reduced by the required amount to allow reduction from the initial group letter designation to the next inferior group designation). Obviously under such conditions, any error must be in the direction of safety.

Such errors are unavoidable in repetitive diving tables use, but the amount of additional time required is more than offset by the extreme flexibility of the system which would be impossible by other methods, and the result has been vastly increased capability in air dives for commercial and military use. An example of such an inequity is apparent when comparing NASA tests results (Edel)[3] with values from the tables derived from this study, and from the U.S. Navy repetitive diving tables for governing repetitive diving at 47 FSW. In each case a dive is made at 47 FSW for 120 minutes followed by a 180 minute surface interval. The maximum permissible no-decompression time according to each source is provided in Table 12.

TABLE 12

SOURCE	REPETITIVE NO-DECOMPRESSION DIVE TIME
NASA Manned Tests	120 minutes
Proposed NASA Repetitive Tables	45 minutes
USN Repetitive Tables	53 minutes

Inspection of the compartment tissue tension values provides the obvious answer to the differences in the repetitive diving time allowed for by the tables, as opposed to that which has been shown in practice to be safe. This specific profile results in fairly low tissue tensions in the slower tissue compartments, but very high (and limiting) tissue tensions in the 40 minute half-time compartment. Yet in each case, assignment must be made to a group with elevated P_{N_2} values in the slowest tissue compartments. In each case, the assigned group will require very long surface intervals before the slowest tissue compartments (which in this case do not affect the decompression obligation) have returned to their initial pre-dive values, as indicated by the tables. However, within 180 minutes, the 40 minute half-time tissue compartment has almost come to equilibrium with the nitrogen partial pressure existing in the air at sea-level pressure and the exposure can be repeated without exceeding limiting values in any compartment.

The difference between the times shown by the U.S. Navy repetitive dive tables and the tables derived from this study is principally due to the fact that the Navy tables were based upon a 120 minute half-time compartment (believed at that time to represent the slowest bodily tissue) while the present study required use of the 360 minute half-time compartment to provide for altitude ascent, during which the slowest bodily tissues will control the reduction of pressure.

****

USE OF TABLES

The initial repetitive dive table showing group letter designations (Table 4) is the counterpart of U.S. Navy repetitive diving Tables 1-10 and is used in the same manner. Any initial dive results in the repetitive group letter designation shown to the right of the dive depths and times. In all cases where depths and/or exposure times are between values shown, the group letter designation for the next greatest depth and/or time is to be used. For changing depth during a dive, Table 8 should be used. If, for example, a diver has spent 90 minutes at 37 FSW, his dive group is E (from Table 4). If he desires to change depth to 47 FSW, reference to Table 8 shows that his equivalent exposure at that depth (group E column) to be 60 minutes. This time is added to whatever time the diver remains at that depth. If for example he stays at that depth one hour, his total exposure time now becomes the 60 minutes equivalent exposure time (resulting from his dive to 37 FSW) plus his actual time at 47 FSW of 60 minutes, for a total of 120 minutes (group H). This is the maximum permissible exposure at that depth, but he may decrease his depth and continue his exposure adding any additional time spent to the appropriate equivalent exposure times shown in the 'H' column.

If a surface interval between dives is used, the above mentioned tables must be used in connection with Table 5 (which has its Navy counterpart in Tables 1-12) when air is used as the breathing mixture, or Table 6 (having no Navy counterpart but performing the functiôn of Navy Tables 1-12 using oxygen instead of air) when oxygen is used. The tables are interchangeable (following the same group letter common for optimum results) during changes in the breathing medium from air to oxygen or the reverse (although for reasons previously given, the latter would not produce maximum advantage) during the surface interval.

An example showing the use of the four tables is as follows:

A dive is made to 47 FSW for 2 hours. From Table 4, the group letter designation is 'H'. The diver now has a three hour surface interval before making the next dive. He spends an hour and 20 minutes breathing air which, from Table 5, shows his new letter to be 'G' at the end of that period. Referring to Table 6 (column H), it can be seen that the equivalent oxygen surface interval would be 25 minutes. He now spends the next hour and 50 minutes breathing oxygen. Adding the time actually spent on oxygen (1 hour + 50 min.) to the equivalent oxygen exposure resulting from the air breathing period (25 minutes) results in a total of 2 hours and 15 minutes. As can be seen from Table 6, a cumulative total of 2 hours and 15 minutes (from a 'H' dive) results in a group letter designation of 'B'. Now referring to Table 8, he can see that his equivalent or residual time at 17 feet is 60 minutes (B column). If he spends two hours at this depth, his total exposure will be that two hours plus the hour residual time at the start of the dive, or 3 hours total. A glance at Table 4 shows a three hour exposure puts the diver in group E.

If an altitude exposure would then be desired (following this dive) Tables 9 and/or 10 would be used. In these tables the group letter (taken from the final dive in the repetitive series) indicates the time required for air and/or oxygen breathing during the surface interval prior to an ascent to specified altitude. Here again, when oxygen and air are both used during the surface interval, maximum benefits will result when air is used as the breathing medium during the initial portion of the surface interval and oxygen breathing is used during the latter portion.

If the foregoing dives series is used in the example of the altitude tables, it can be seen (from Table 9, column E) that after 15 minutes a cabin pressure altitude of 10,000 feet can be attained. If the surface interval is extended to 80 minutes, the subject can be exposed to a cabin pressure altitude of 12,000 feet, and after a two and a half hour surface interval, a flight to a cabin pressure altitude of 13,000 feet is permissible.

Naturally, greater cumulative exposures require proportionally longer surface intervals to permit exposure to desired altitudes. If, for example, 5 hours is spent at 37 FSW, the diver's repetitive group letter would be 'O'. Following such a dive (or the equivalent in repetitive exposures), it would require a 3 hour surface interval to permit exposure to a cabin pressure altitude of 8,000 feet (Table 9). If, however, an additional 110 min. were spent breathing oxygen, the total equivalent oxygen time would be 90 minutes (the equivalent oxygen time to denitrogenate sufficiently to reach 8,000 feet) plus 110 minutes = 200 minutes. As can be seen from column 'O' on Table 10, this would permit attaining a cabin pressure altitude of 13,000 feet.

If needed, the table can be continued in flight. In the latter case, an additional 70 minutes of oxygen breathing would permit an ascent to 15,000 feet cabin pressure altitude. If the subject continued breathing oxygen during his flight, after 70 minutes flight time he could increase his cabin pressure altitude to 15,000 feet.

As previously mentioned, the surface interval credit tables resulting from this study (as in the U.S.N. counterpart) are overly restrictive in the case of a 47 FSW exposure, wherein a half-time tissue of 40 minutes controls or limits said exposure. This is, however, an unusual case within the depth-time range considered in this study (although more common with respect to U.S.N. tables which are required to encompass a greater area of depth-time combinations). This results from very high and limiting P_{N_2} values in the 40 minute half-time compartment coupled with comparatively low P_{N_2} values in the slower tissue compartments. Running this specific profile through the computer grouping program resulted in the following group letter values, shown in Table 13:

TABLE 13

DEPTH	TIME	GROUP
0	0	-
47	120	H
0	180	F
47	120	M
0	900	C
47	120	J
0	180	G
47	120	N

Applying these group letter designations to altitude ascents with the tables developed as a result of this study shows good conformity with the results of Edel in previous experiments.[1,3] Use of these group letter values (in lieu of present recommendations covering this specific exposure) will permit interchangeable use of air and oxygen during surface intervals prior to flight and increase the options for cabin pressure altitudes which may be utilized by previous recommendations.

MEASUREMENT OF CABIN PRESSURE ALTITUDES

The tables are related to actual pressure to which the subject is exposed. Obviously, accurate pressure readings must be obtained to provide maximum benefit and safety with this, or any other, table involving decompression procedures. If the gauges used to determine cabin pressure altitude during flight have an error band, the flight altitude must take this possible error into account. If the accuracy of such gauges is ± 2,000 feet, then 2,000 feet must be added to the gauge reading to provide maximum safety ot personnel engaged in such procedures. If such an error band exists in existing aircraft utilized in connection with such profiles, units of greater accuracy should be installed as replacements for existing gauges, or a supplemental gauge with required accuracy should be incorporated to provide the most advantageous use of altitudes during flights.

The elevation of 680 feet at the Marshall Space Flight Center was taken into account in providing tables for this program by 'normalizing' the tables used to conform with existing decompression and flight procedures which have been shown to be satisfactory over the years.

SUMMARY

Using a Wang Series 2000 computer, repetitive diving tables were developed through this program patterned after the U.S. Navy Repetitive Diving Tables in terms of application and format. The tables were constructed specifically for NASA's simulated weightlessness training program at the Marshall Space Flight Center in Huntsville, Alabama. The tables provide for 8 depth ranges covering depths from 7 to 47 FSW, with exposure times of 15 to 360 minutes.

These tables were based upon an 8 compartment model using tissue half-time values of 5 to 360 minutes and Workmanlike M-values for control of the decompression obligation resulting from hyperbaric exposures. Supersaturation ratios of 1.55:1 to 2:1 were used for control of ascents to altitude following such repetitive dives. Adequacy of the method and the resultant tables were

determined in light of past experience with decompression involving hyperbaric-hypobaric interfaces in human exposures. Using these criteria, the method showed conformity with empirically determined values. In areas where a discrepancy existed, the tables would err in the direction of safety.

Increased flexibility of repetitive diving tables was obtained through the development of surface interval decompression tables for use with oxygen breathing which may be used separately or in connection with the surface interval credit tables for air breathing medium. Additional tables were also provided for determining the surface interval required (using air and/or oxygen breathing mediums) prior to ascent to altitudes of 5,000 to 17,500 feet which may, if desired be continued in flight.

While every effort has been made to provide tables which are safe, while offering minimum restrictions to hyperbaric-hypobaric profiles, no tables can be considered to provide all required assurances of safety with respect to decompression sickness until such tables have been verified through tests involving human subjects. It is therefore recommended that these tables be subjected to manned tests designed to verify the adequacy of the system in situations covering the profiles adjudged to present the greatest degree of relative risk.

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