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DECOMPRESSION RISKS

IN

SUCCESSIVE HYPERBARIC-HYPOBARIC EXPOSURES

by

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ABSTRACT

As part of their training program, astronauts are required to carry out "no-decompression" dives at the bottom of a tank filled with 40 feet fresh water at the Marshall Space Flight Center while wearing pressure suits inflated to 3.5 psi above ambient pressure. These dives may be repeated twice daily for approximately five consecutive days. According to accepted techniques for calculating decompression tables, a diving schedule of two hours in the morning and two hours in the afternoon separated by a three hour surface interval does not incur a significant probability of decompression sickness. A similar work schedule can be safely followed on the second and successive days if a minimum surface interval of 16 hours separates the workdays. Calculations further indicate that these astronauts could safely fly home without incurring decompression sickness if the maximum aircraft cabin pressure is maintained at the equivalent of 10,000 feet altitude, and each day's diving profile includes the following schedule of surface intervals:

Diving Day	Dive	Surface Interval Prior to Ascent to Altitude	
		8,000 ft. altitude	10,000 ft. altitude
1	1st	1-1/2 hours	2-1/2 hours
1	2nd	2-1/2 hours	4 hours
2,3,4, etc.	1st	2 hours	3 hours
2,3,4, etc.	2nd	3 hours	5 hours

INTRODUCTION

Repeated underwater pressure exposures of human subjects, and underwater pressure exposures followed by altitude pressure exposures, are assuming increasingly important roles in the present-day experimentation among various scientific disciplines.

The present investigation is an analysis of the decompression-sickness hazards that are encountered by those subjects who are exposed to successive hyperbaric exposures or alternating hyperbaric-hypobaric exposures, and what decompression procedures are the most effective in eliminating altogether or greatly reducing such hazards.

The NASA Manned Spacecraft Center requested an analysis of the decompression sickness probability in astronauts diving in a tank filled with 40 feet of fresh water as part of a training program at the Marshall Space Flight Center in Huntsville, Alabama. The astronauts wear a pressure suit inflated to a degree not exceeding 3.5 psia above ambient pressure, and their plan has been to work up to a maximum of three hours in the morning and three hours in the afternoon, the workload being repeated on a maximum of five successive days.

The dives are no-decompression dives, and the analysis is to evaluate the maximum safe time the astronauts can spend under seawater pressure without developing symptoms of decompression sickness upon surfacing, and the minimum safe surface interval between the morning and afternoon dives. Also to be analyzed are the limitations imposed by repetition of the workload on five consecutive days with the approximate 15 or 16 hours spent at surface pressure between the workdays.

Evaluation is also to include the possibility of decompression sickness when, following the workload outlined above, the astronauts then fly in an aircraft whose cabin may be pressurized at an equivalent altitude of 5,000 to 25,000 feet.

Special account is to be taken of the 680-foot altitude of the Marshall Space Flight Center Site.

PHYSIOLOGY OF DECOMPRESSION SICKNESS

Definitions.

Decompression sickness may be defined as those signs or symptoms related to decompression at such a rate that it causes gaseous bubbles to develop in the body which can produce pain, debilitation, or loss of physiological function. The four general classifications of decompression sickness are symptoms affecting the central nervous system (CNS), chokes, bends, and skin manifestations.

Needless to say, the importance of decompression-sickness symtomatology in a space crew would depend upon type and severity of the attack. In general, CNS manifestations are debilitating, and would jeopardize the health and welfare of the afflicted individual to such an extent that immediate treatment would be required. However, CNS symptoms are not considered likely in the type of dive-altitude profiles involved in the present investigation.

Chokes impairs and restricts respiration, and completely incapacitates the victim. It must be ameliorated within a few minutes or its effects might be fatal. Chokes is, however, an uncommon occurrence.

Skin manifestations are clinically interesting and subjectively intriguing. They would not, however, threaten the normal completion of a mission or training program such as the one under consideration here.

Bends--the pain whose primary target is the joints--can remain at a barely discernible level, or can develop to such severity that even massive doses of morphine will not bring relief. The symptoms can develop with extreme rapidity, or gradually increase in intensity over a period of many hours. Bends symptoms may occur during the actual reduction in pressure, or may not become manifest until many hours after pressure has been reduced. Symptoms may be tolerable and remit with the passage of time at surface pressure breathing either air or oxygen or require recompression therapy.

Although spontaneous relief is possible, treatment in all cases of decompression sickness (with the exception of skin manifestations) should be instituted without delay to prevent the possible development of a more serious condition with the passage of time.

Unfortunately, it is not possible to predetermine with any degree of certainty the probable course bends symptoms will take, once they appear, since so many factors are involved. However, in general, of all the possible symptoms of decompression sickness of a serious nature that can result from the present type of dive-altitude profiles, bends is the most probable.

Variations in Susceptibility to Decompression Sickness.

A maximum safe change in pressure is limited only by the probability of decompression sickness; and to determine the level of pressure providing safety against an attack for nearly all personnel exposed under specific circumstances--especially for an unselected group of individuals--requires substantial testing. It must always be borne in mind that procedures which are eminently safe for the vast majority of individuals may be inadequate to protect those few persons who are unusually susceptible to decompression sickness. To include the latter within the scope of safe decompression procedures would be unreasonably restrictive to those less susceptible. In general, however, the least pressure change in any test profile incurs the lowest probability of decompression sickness, and conversely, the greatest pressure change produces the greatest probability.

Accuracy in predicting decompression sickness is hampered primarily by ariations in response to a given pattern of decompression among individual subjects, and also within the same individual.[1] In the latter instance, there is involved the statistical probability that symptoms will occur. There is also involved the possible occurrence of minor bodily changes from time to time that will render the subject more or less liable to an attack of decompression sickness.

With respect to bends, which is of primary consideration in the present investigation, group studies of variation in response to a given decompression pattern have revealed a correlation among several factors. Investigations made by the United States Army Air Force[2] during World War II showed that, as a group younger men (1) are considerably more resistant to bends at altitude, and (2) require less preoxygenation time for protection against bends than older crew members do.[3]

However, there are significant variations in resistance to bends among members of same age groups, which may possibly be attributed to differences in such factors as body build and quantity of body fat. Correlations between susceptibility to bends and ratios of weight to height have also been established.[4] The constitutional factors that appear to render one individual more susceptible to bends than another may, in fact, be simply the difference in the tissue half saturation time of nitrogen among individuals. It has been observed in testing decompression profiles "acclimatized" subjects--those who have previously been exposed to a number of pressure changes within a given period--do not have the same susceptibility to bends that "unacclimatized" subjects do.

Nitrogen Uptake and Elimination in Bodily Tissues.

Of the several inert gases contained in the earth's breathing atmosphere, the only one of special significance in this study of decompression sickness 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, do not play a significant role in these considerations.

Bodily tissues respond to increased or decreased nitrogen partial pressure 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 in a bodily tissue that is reached after a specific time interval, following a change in the nitrogen content in the breathing medium, is expressed in the following equation:

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

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

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

P_a: Partial pressure of nitrogen in FSWA in the breathing medium.

e: Base of natural logarithms.

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 the 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 of the partial pressure gradient formed. A "fast" tissue may reach this value in several minutes, whereas a "slow" tissue may take several hours to achieve it.

The percentage of nitrogen taken up or eliminated from a given tissue is determined by the time (t) that the tissue is exposed to the change in nitrogen partial pressure. The magnitude of this change, for given values of k and t, is determined by the gradient $P_a - P_o$, which is the difference between partial pressure of nitrogen in the breathing mixture and in the tissues.

Supersaturation Ratio.

Supersaturation may be expressed as the ratio of the partial pressure of nitrogen in the bodily tissues to that of the ambient pressure. During decompression, the concern is with a state wherein ambient pressure has been reduced to such a degree that the nitrogen in solution in the tissues is in excess of the tissues' normal level of saturation with respect to pressure--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 manners: (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) a breakdown of the supersaturated solution into stable gas and liquid phases will occur, 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. The probability of bubble formation and subsequent development is dependent upon the degree of nitrogen supersaturation in a specific half-time tissue.

In conformance with accepted diving interpretations, the supersaturation ratio is generally taken to be the ratio existing at the time the diver arrives at the new water depth or its equivalent pressure level. For example, if a diver's tissues are saturated to a nitrogen partial pressure of four atmospheres and he is then very rapidly decompressed to two atmospheres, the supersaturation ratio will be 2:1 upon his arrival at a new pressure. The greater this ratio is, the higher the probability is that bubble formation and decompression sickness will result. If on the other hand, the ratio is too small, the rate of nitrogen elimination becomes so slow that the safe decompression procedures are unrealistically restrictive. The objective during decompression within specific operational conditions, therefore, is to determine a ratio that will be physiologically safe, but not unduly restrictive.

The ratio to be used with respect to a specific tissue depends on such factors as the inert gas (or gases) used, depth, and tissue half time. In general, an allowable or safe supersaturation ratio decreases as the tissue half time increases. For any given half-time tissue, furthermore, the supersaturation ratio decreases as depth is increased. By convention, the bodily tissue that takes up and eliminates nitrogen most rapidly is considered to have a one-half saturation time of five minutes. This tissue will tolerate a supersaturation ratio of approximately 3:1 upon surfacing. The slowest tissue is assumed to have a 360-minute half time (for nitrogen) with a maximum supersaturation ratio upon surfacing of about 1.5:1.[5] Studies indicate that there may be great differences in the nitrogen uptake and elimination times among individuals, and one would expect corresponding individual variations in the maximum safe supersaturation ratios for the slowest tissue as well.

ANALYSIS OF DECOMPRESSION SICKNESS RISKS IN HYPERBARIC AND HYPOBARIC EXPOSURES AT HUNTSVILLE, ALABAMA

In the analyses contained in the following subsections, certain assumptions are always made. First of all, it is assumed that during the 48-hour period immediately prior to the initial dive, the subjects have not undergone nitrogen hyperbaric exposure. The nitrogen partial pressure in the bodily tissues is therefore assumed to be in a state of equilibrium with that in the sea-level atmosphere. It is further assumed that the subjects have been free from any symptoms of decompression sickness for a minimum period of two weeks prior to the initial dive, since sites of tissue damage caused by a recent attack of decompression sickness might become focal points for bubble formation upon subsequent decompression.

Marshall Space Flight Center Diving Tank.

Virtually all decompression tables in the United States refer to pressure in terms of feet seawater depth (FSW). It is therefore expedient to convert all references to pressure units accordingly. One foot of seawater is equal to 1/33rd of the pressure of one atmosphere, or 0.445 psi. One foot of fresh water (FFW) is equal to 1/34th of the pressure of one atmosphere, or 0.433 psi.

Since the tank at Marshall Space Flight Center (MSFC) is filled with 40 feet of fresh water, it is necessary to convert its FFW depth to the equivalent FSW depth; 40 FFW equals 39 FSW, or 17.32 psi. The astronauts' 3.5-psi suit pressure is equal to approximately eight feet of seawater pressure, which in addition to the depth of water in the tank exerts a total pressure on the astronaut that is equivalent to 47 FSW. The elevation at the Marshall Space Flight Center is approximately 680 feet, which is equal to .7 FSW less than 33 FSW, the equivalent pressure of a standard atmosphere.

The subjects in the present investigation return to the same surface pressure after their dives that they started from. It is therefore reasonable to designate a differential pressure of 47 FSW as being applicable to these dives, and to make necessary denitrogenation calculations on the basis of this pressure differential and referenced to sea-level pressure.

This adjustment provides realistic margins of safety in denitrogenation profiles for personnel resident at Huntsville, and for those who live in or commute to and from an area of lesser elevation than that of the Marshall Space Flight Center. For personnel who live in the environs (or equivalent) of the Marshall Space Flight Center, the rate of denitrogenation between successive hyperbaric exposures will be greater, and hence more favorable to the avoidance of decompression sickness.

Nitrogen Tissue Tensions During Hyperbaric Exposure to 47 Feet. To avoid decompression sickness during the MSFC dives, it is advisable to restrict pressure exposures to "no-decompression" dive limits--that is to say, dives must not exceed a length of time at 47-FSW depth that would prohibit safe direct ascent to surface, so that neither incremental decompression stops nor use of a surface recompression chamber is required.

The "no-decompression" depth-time limits as they appear in the U. S. Navy Diving Manual (NAVSHIPS 250-538), are given below:[6]

Depth (FSW)	Maximum No-Decompression Time (minutes)
100	25
90	30
80	40
70	50
60	60
50	100
40	200
35	310

Plotting these points on a graph produces a curve illustrating the depth-time limits in no-decompression dives (see Figure #1). Although standard decompression tables in the United States and Great Britain are, for the sake of convenience, generally given in multiples of 10 feet, exposure limits for depths between the increments shown in the depth-time curves of diving manuals can be accurately estimated.

The depth-time curve shown in Figure #1 (solid line) indicates that a bottom time of 120 minutes can be considered safe for a no-decompression

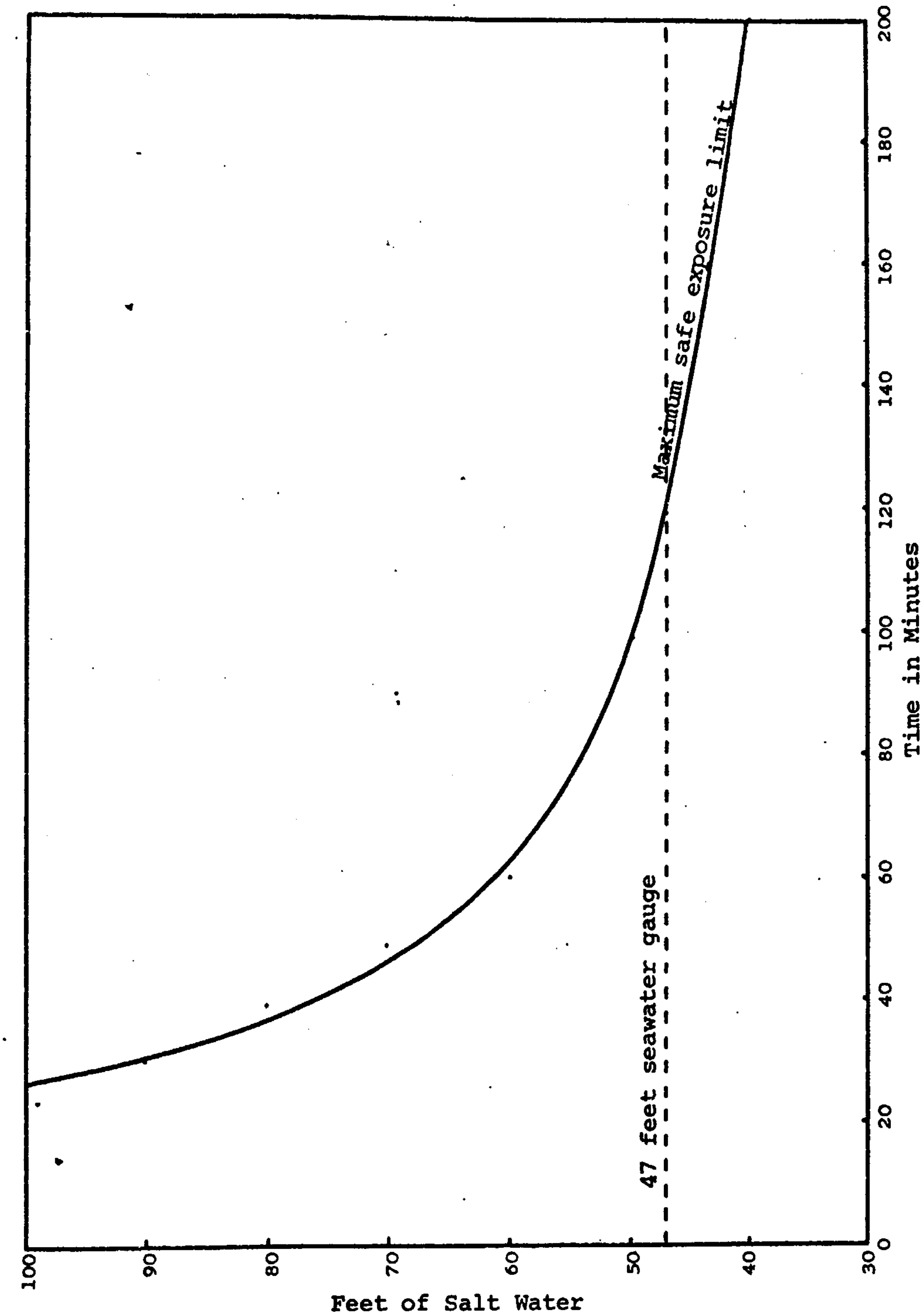

Figure 1. Air no-decompression curve.

dive to 47 feet (dashed line). Calculations suggest that the partial pressure of nitrogen in the controlling tissues (those tissues that limit decompression because of the slow rate at which they eliminate nitrogen) is about the same, whether it is a 47-foot dive lasting 120 minutes or a 50-foot dive lasting 100 minutes. Both dives are considered to be well within acceptable safety limits. The three-hour bottom time suggested as maximum for the dives at MSFC will not, however, permit direct ascent to surface, and must therefore be reduced to a maximum of 2 hours.

Prior to exposure to seawater pressure, a subject's tissues are assumed to be in a state of equilibrium with the partial pressure of the nitrogen in the atmosphere at sea level. Breathing air at the pressure of one atmosphere (which equals 33 FSW) produces a partial pressure of nitrogen in the tissues equal to that of 26 FSW pressure--i.e., 79% of the total pressure of 1 atm.

Gauge pressure of 47 FSW is equal to 80 FSW absolute, i.e., 47 FSW + 33 FSW (1 atm) equals 80 FSW absolute. This 80 FSW abs. multiplied by the 79% nitrogen content of the breathing mixture equals 64 FSW (.79 x 80 FSW = 64 FSW). Breathing air at 47 FSW, a subject is exposed to a nitrogen partial pressure of 64 FSW. The partial-pressure gradient is the difference between the nitrogen content of the bodily tissues and that of the inspired breathing medium (P_a-P_o). When the astronaut is first immersed in 40 FFW wearing a pressure suit inflated to 3.5 psi above ambient pressure, and is breathing air, the nitrogen partial pressure gradient is 38 FSW--i.e., 64 FSWA (absolute partial pressure of nitrogen in the air at 47 FSW gauge) minus 26 FSW (nitrogen pressure in the tissues at sea level) equals 38 FSW. The rate of nitrogen uptake in the bodily tissues is calculated for 20-, 40-, and 80-minute half-time tissues on the basis of a gradient of 38 FSW, and the results are plotted against time in the dive profile of Figure #2.

After two hours at 47 FSW, the diver returns to surface and the gradient (P_a-P_o) is reversed, providing an outward gradient for elimination of nitrogen from the bodily tissues to the partial pressure of nitrogen in the atmosphere at sea level (26 FSW).

Successive Hyperbaric Exposures.

Because of the requirements made of the astronauts at Marshall Space Flight Center, attention must be directed to the physiological effects on the human organism of successive dives interspersed with sea-level exposures. Following a 47-FSW dive and direct ascent to surface at the rate of 60 feet a minute, a three-hour surface interval will cause the faster tissues to resume approximately the same nitrogen content that they had prior to the initial dive. The slower tissues will contain more nitrogen than they did prior to the dive, but not so much that they must be taken into special consideration in calculating recompression to sea-level pressure following a second exposure comparable to the first one. A second dive may then be undertaken and, according to calculations, a 120-minute exposure at the same depth will be safe against decompression sickness. The reason is that the slowest tissues will not have accumulated enough nitrogen at the end of the second pressure exposure to be limiting and the faster tissues will not appreciably have exceeded the nitrogen values

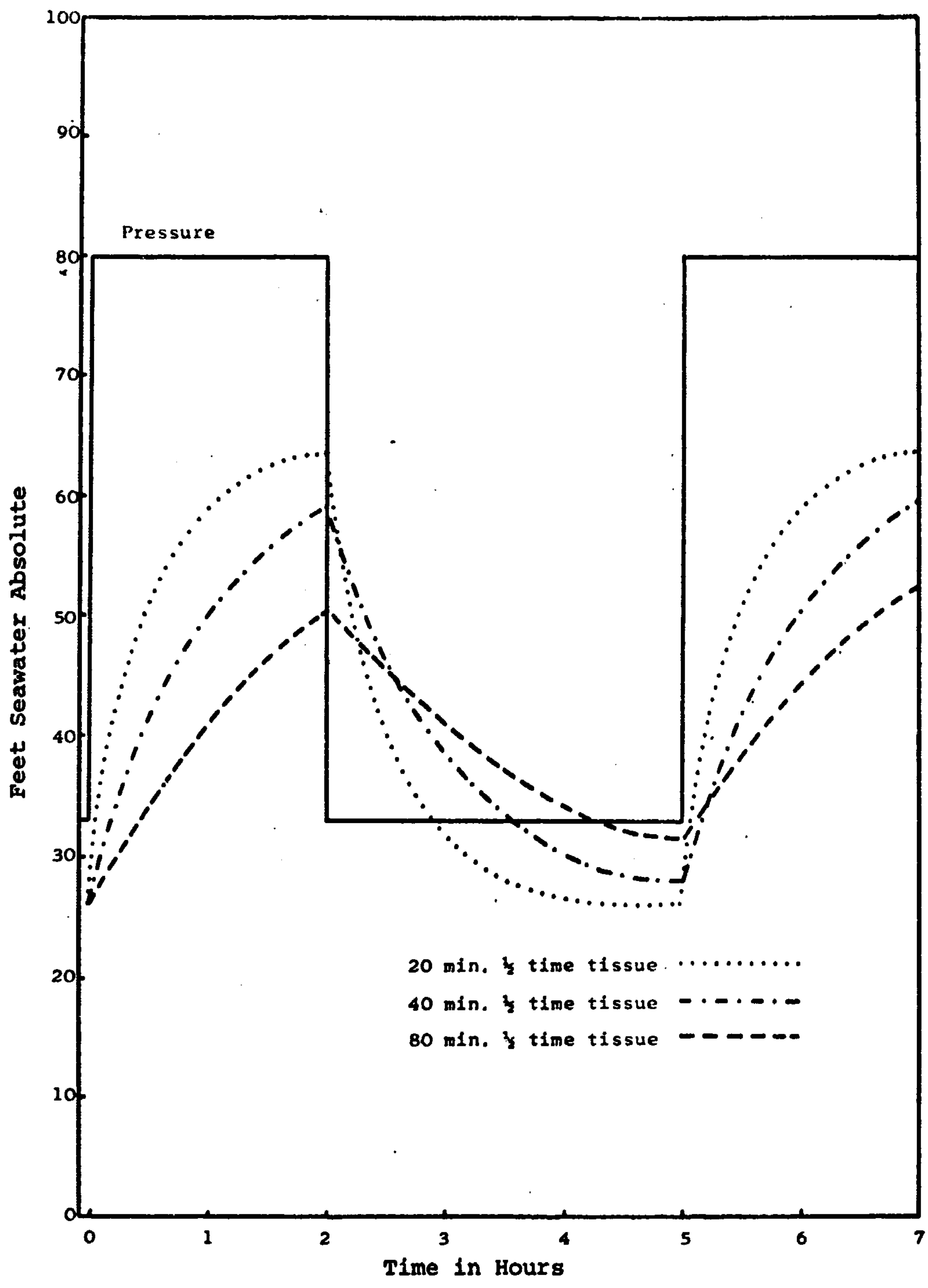

Figure 2. Partial pressure of nitrogen in 20-, 40-, 80-, minute half-time tissues showing rate of saturation and desaturation.

resulting from the initial exposure (see Figure #2). In short, it is safe to make a dive to 47 feet for 120 minutes with a direct ascent (at the rate of 60 feet per minute) to the surface, followed by a surface interval of three hours, after which a second dive could be made for the same depth and time as the initial one.

As can be seen in Figures #3 and 4, the three-hour surface interval has little effect on nitrogen elimination in the slower tissues. The most noticeable example of this is the slowest bodily tissue (assumed to have a 360-minute half time), which contains appreciably more nitrogen at the start of the second dive than it did prior to the initial pressure exposure.

If a 16-hour sea-level interval (between one workday and the next) elapses prior to a third dive some residual nitrogen in the tissues accumulated from the previous two dives will still be present. This accumulation amounts to an increase of 7-1/2% nitrogen partial pressure in the slowest tissue at the start of the third dive over that in the slowest tissue before the first dive. A repetition of the previous day's schedule--that is, two dives to 47 feet separated by a three-hour surface interval--following a surface interval of 16 hours, will result in higher nitrogen partial pressure in the slowest tissue upon surfacing after the second day's dives (third and fourth dives) than existed after the two dives made on the first day (see Figure #4). Furthermore, the nitrogen partial pressure in the slowest tissue after a second 16-hour surface interval (following the fourth dive) is not appreciably higher than that which existed in the slowest tissue after the 16-hour surface interval following the second dives.

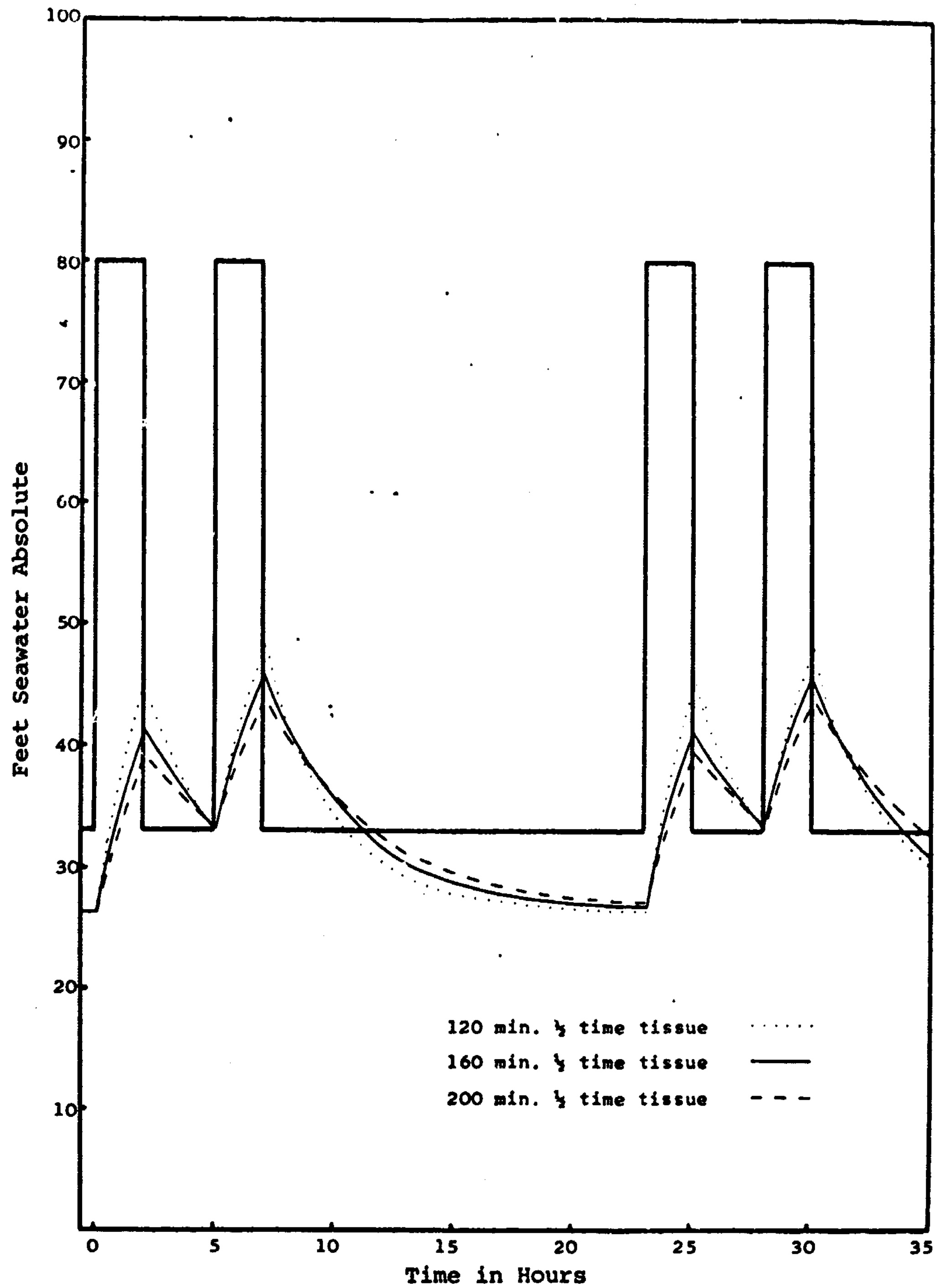

Figure 3. Partial pressure of nitrogen in 120-, 160-, 200-minute half-time tissues showing rate of saturation and desaturation.

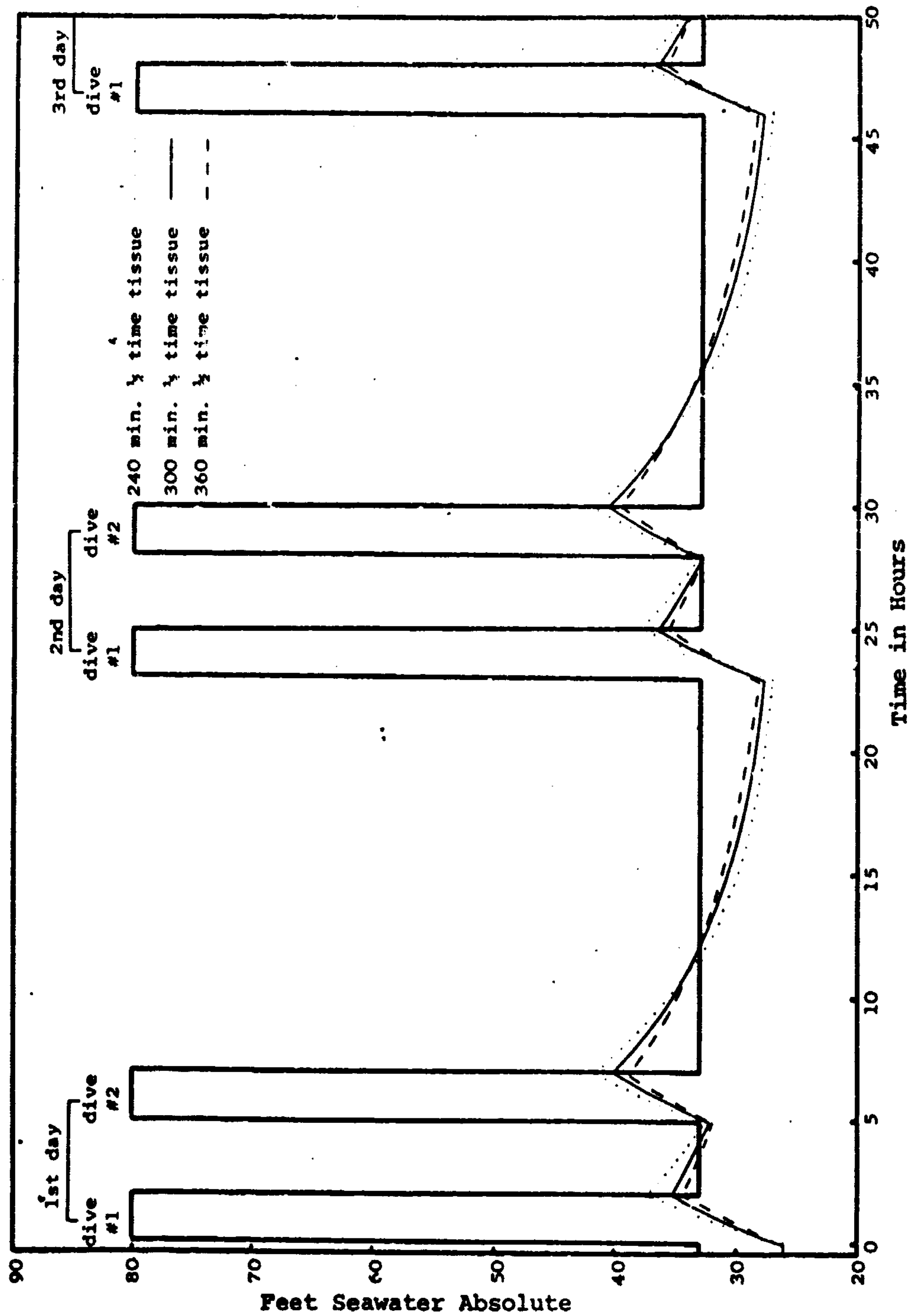

Figure 4. Partial pressure of nitrogen in 240-, 300-, 360-, minute half-time tissues showing rate of saturation and desaturation.

Further repetition of this same diving schedule causes little further change in the nitrogen tension of the slowest tissue. The nitrogen values in the slowest tissue on the third, fourth and fifth days, on which identical diving schedule are followed, are essentially the same as those attained during the second day. Under these conditions, the nitrogen partial pressure in the slowest tissue never attains such magnitude as would prohibit a direct ascent to surface. The slowest tissue can, however, limit further reduction in pressure when an ascent to altitude is made following one of the series of dives under consideration. For this reason, accurate calculations of the nitrogen tissue tension in the slowest tissue are necessary.

Hypobaric Exposure Following Hyperbaric Exposure. The partial pressure of nitrogen in the various tissues permit, according to accepted pressure-exposure calculations, a safe ascent to surface following any of the dives under consideration. Upon surfacing, however, nitrogen tension is still too high to permit direct ascent to aircraft in-flight altitude without the risk of decompression sickness. During the interval spent at sea level, the tissues begin to denitrogenate and commence the process of attaining nitrogen equilibrium with the sea-level atmosphere. The tissues that took up nitrogen the most rapidly will eliminate nitrogen at an equally rapid rate. Conversely, the slower tissues, although they contain much less nitrogen than the faster ones do, eliminate nitrogen at a slower rate after surfacing.

Flight crews have not usually been exposed to hyperbaric pressure in the crucial time interval prior to flight, so that the nitrogen content of their bodies and of the sea-level atmosphere are in a state of equilibrium. Experience gained from actual flights and from altitude chamber tests has shown that a rapid ascent from sea level to 16,500 feet is eminently safe against decompression sickness, assuming that there has been no recent hyperbaric exposure. The reduction in pressure to 16,500 feet (7.75 psia) with the nitrogen partial pressure in the bodily tissues at sea level (11.6 psia) results in a supersaturation ratio of about 1.5:1. This ratio is equivalent to a return to sea level after an infinite stay, during which time air is breathed.

30 FSW + 33 FSW (1 atm.) = 63 FSWA;

63 FSWA x .79 (percentage N_2 in air) = 49.8 FSWA;

49.8 FSWA = N_2 pressure in tissues after infinite dive at 30 FSW;

49.8 FSWA ÷ 33 FSW = supersaturation ratio of 1.5:1.

The 1.5:1 nitrogen supersaturation ratio can be considered safe for the slowest tissue, which is most restrictive in the context of the hyperbaric-hypobaric exposure profiles under condieration in the present study. Faster tissues can tolerate higher supersaturation ratios.

Upon a diver's return to surface after a two-hour exposure at 47 FSW, his faster tissues attain supersaturation ratios in excess of 1.9:1. In standard decompression tables, even higher supersaturation ratios have been safely utilized for fast tissues under certain conditions.

As has been pointed out (see Figure #2, #3, and #4), the fast tissues eliminate nitrogen very rapidly, leaving the slower tissues wit' the highest nitrogen tensions after a short time at surface pressure. Consequently, the surface time interval prior to ascent to altitude can be calculated according to these dive profiles by simply applying the 1.5:1 ratio to the tissue containing the highest nitrogen partial pressure at any given time, without appreciably increasing the minimum safe surface interval.

In tests to determine the necessary surface intervals following pressure exposures prior to an ascent to altitude, it was noted that the faster tissues with half times between 10 and 40 minutes attained supersaturation ratios of 2:1 or more upon arrival at an altitude of 8,000 feet.[7] The supersaturation ratios in these tissues did not provoke bends. When the 80-minute half-time tissues were involved and the supersaturation ratio was 2:1 on arrival at 8,000 feet altitude, mild bends were experienced by two out of ten test subjects.

Surface Interval Prior to Flight After Diving.

Since the supersaturation ratio in a given tissue (or tissues) is maximal or near maximal when a diver surfaces, it is obviously not safe for him to undergo a further reduction in pressure until some degree of denitrogenation has taken place. Furthermore, since 48 hours must elapse before the bodily tissues reach an approximate state of equilibrium with the nitrogen partial pressure in the air at sea level, an ascent to an altitude of 16,500 feet (with a nitrogen partial pressure in the bodily tissues of 26 FSW) cannot be safely attempted any sooner. We are then concerned with ascent to maximum altitudes that can be safely made between the time the diver reaches surface and 48 hours after he has reached surface.

Since the rate of nitrogen elimination is exponential, it is greatest immediately after the diver has surfaced from a dive, the rate progressively decreasing thereafter. As a result, ascent to a relatively low altitude may safely take place after a comparatively short surface interval, but longer time intervals are required before ascent to higher altitudes may be attempted. For example, if one hour is required on surface to desaturate the bodily tissues to the degree that an ascent to an 8,000-foot altitude may be safely attempted, allowing an average denitrogenation time on surface of 7.5 minutes per 1,000 feet of altitude, twice that length of time is required to make an ascent to 10,000 feet with the same degree of safety (allowing an average denitrogenation time on surface of 15 minutes per 1,000 feet.)

Upon a diver's surfacing, the nitrogen partial pressure in his slowest tissues (which ultimately limit ascent to altitude) will be higher during the dives that follow the initial one. A separate analysis must therefore be made for each dive in the series until the point is reached at which further repetitions of the pressure profiles cease to produce a cumulative effect in increasing the load of nitrogen partial pressure in the slowest tissue; or until that point in the series is reached at which the surface interval is 48 hours or more. As Figure #4 illustrates, the nitrogen tissue tensions in the slowest bodily tissue remain relatively the same during dives taking place after the second day in the diving program presently under investigation. It is therefore necessary to consider only the nitrogen accumulated during the first two days' dives.

Obviously, the nitrogen tension in the bodily tissues will be lower upon surfacing after the first dive of the series than after any other. Calculations indicate that after the initial two-hour dive to 47 feet, ascent to 8,000 feet will be safe following a surface interval of one and a half hours; and ascent to 10,000 feet will be safe following a two-and-a-half hour surface interval.

If a second two-hour dive is made on the first day of the diving program, and a three-hour surface interval separates the two dives, the slowest tissues will contain higher nitrogen tensions than they did prior to the initial dive (see Figure #4). After the second dive, a minimum surface interval of two and one-half hours is indicated by the calculation before an ascent to 8,000 feet can be made safely, and four hours prior to 10,000 feet.

The slowest tissues will lose most of the excess nitrogen accumulated in the first day's diving profile during the minimum 16-hour surface interval before the second day of the diving program begins. The slowest tissues will not, however, have returned to a state of nitrogen equilibrium with the atmosphere (see Figure #4). After this 16-hour surface interval, a third two-hour dive (the initial dive of the second day) can safely take place. According to calcualtions, two and one-half hours after this dive is completed, ascent to 8,000 feet can be safely made; or three hours after the dive, ascent to 10,000 feet can be attempted without undue threat of decompression sickness.

If a second two-hour dive is made on the second day, with an intervening surface interval of three hours, the slowest tissue will, upon the second surfacing, attain maximum nitrogen tissue-tension values for the series of dives under consideration. An ascent to 8,000 feet altitude may safely be made three hours after surfacing from this dive, and ascent to 10,000 feet after five hours.

The first two-hour dive made on the third, fourth, or fifth day will produce approximately the same nitrogen tissue tensions that were attained after the first dive of the second day. Safe ascent to altitude following the first dive of the third, fourth, or fifth day will require the same surface interval that preceded ascent after the first dive of the second day. Any second dive made on the succeeding days will cause approximately the same nitrogen tissue tensions attained after surfacing from the second day's second dive. These second dives on the succeeding days will also require the same surface interval prior to an ascent to altitude as that required after the second dive of the second day.

Oxygen Breathing Prior to Ascent to Altitude.

Such factors as transportation time from the diving site of the airfield, changing from diving gear to street wear, debriefing, and flight preparations combine to affect the minimum surface interval between the time the subject concludes his dive and his exposure to altitude. The time thus consumed is ordinarily about two hours. Surface intervals between diving and flying, therefore, that do not exceed two hours are not of interest in a discussion of means of shortening the surface decompression period. As can be seen from the chart in RECOMMENDATIONS AND CONCLUSIONS, there is little, if any, advantage to be gained by reducing the surface interval following the initial dives of each day in the present investigation, or when ascent to altitude following them is to a maximum of 8,000 feet. The second dives of the day do, however, involve appreciably longer surface intervals before safe ascent can be made to 10,000 feet altitude, and consideration of effective means of shortening the surface interval in these cases is worthwhile.

Oxygen breathing accelerates the rate of nitrogen desaturation from the bodily tissues by producing the maximum obtainable gradient between the nitrogen partial pressure in the bodily tissues and that in the inspired breathing mixture ($P_a - P_o$). The surface interval may therefore be significantly reduced via oxygen breathing. For example, in the instance of ascent to 10,000 feet following the second dive of the second or any succeeding day, the five-hour surface interval during which the diver breathes air can be reduced to two hours if he switches to continuous oxygen breathing.

Variations or Loss of Cabin Pressure.

The proposed schedules are based upon in-flight pressures to which the astronauts will be exposed following a dive or series of dives. Successful completion of such a flight without incidence of decompression sickness depends in part upon accurate control of cabin pressure. If cabin pressure is maintained at a higher altitude than that specified as being safe following a dive, a higher supersaturation factor than the one calculated for will result, and hence the risk of decompression sickness increases. In commercial passenger flights, cabin pressure is maintained at an altitude of 8,000 feet or less.

Military aircraft are not so restricted in the matter, and cabin pressure is, in part, dependent upon aircraft altitude and accuracy of the cabin pressure regulator. Since there is a permissible margin of error in cabin-pressure regulators and indicators (AF62-3645 for example, allows a variation of ± 1,000-foot cabin pressure setting at 8,000 feet), possible fluctuation must be taken into account. The aircraft cabin altitude selected must be at least 1,000 feet less than the maximum altitude specified for a given surface interval.

Should cockpit pressurization fail but be restored within a minute or so, it is extremely unlikely that decompression sickness will result. This is particularly true toward the end of the flight, since denitrogenation will have been taking place in the intervening time interval. If, however, the subject is exposed for more than a few minutes to a lower pressure than the one indicated by the schedules set out in the chart in RECOMMENDATIONS AND CONCLUSIONS (particularly at the beginning of the flight), decompression sickness is a probable consequence. Hence, efforts should be directed to effecting a return to surface as soon as possible to forefend such a possibility.

RECOMMENDATIONS AND CONCLUSIONS

1. Calculations indicate that a dive from a 680-foot elevation to a depth of 40 FFW while the diver wears a pressure suit inflated to 3.5 psi in excess of ambient pressure, for a period not to exceed two hours and followed by a direct ascent to surface may be safely made. The first dive may then be followed by a second one identical to it after a surface interval of three hours.

2. A surface interval of 16 hours after the second dive is required before a repetition of the foregoing schedule is attempted.

3. This schedule may be repeated indefinitely, with a three-hour surface interval following every odd-numbered dive, and a 16-hour surface interval following every even-numbered dive.

4. Any dive made after a 48-hour surface interval must be considered to be the first dive of a new series.

5. The surface intervals prior to an ascent to altitude that are safe against the development of decompression sickness is tabulated in the following chart:

Diving Day	Dive	Surface Interval Prior to Ascent to Altitude	
		8,000 ft. altitude	10,000 ft. altitude
1	1st	1-1/2 hours	2-1/2 hours
1	2nd	2-1/2 hours	4 hours
2,3,4, etc.	1st	2 hours	3 hours
2,3,4, etc.	2nd	3 hours	5 hours

6. To assure conformance with altitude limitations for a specified surface interval, the maximum altitude possible indicated by the altitude and variation of the pressure regulator should be used. As an example, if the aircraft's cabin altimeter indicates an altitude pressure equivalent to 8,000 feet, a plus error of 1,000 feet must be assumed, and a surface interval applicable to the next greater altitude--i.e., 10,000 feet must be used.

7. The schedules recommended herein should be validated by testing them in a dry chamber to simulate the suggested pressure-altitude profiles.

8. It is further recommended that more complete diving tables be calculated for depths less than 40 FFW, and for cabin altitudes of less than 8,000 feet and more than 10,000 feet.