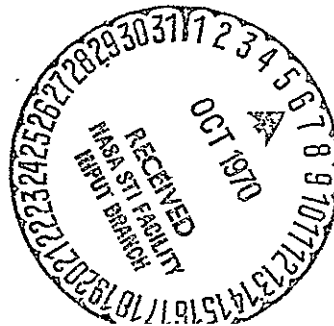


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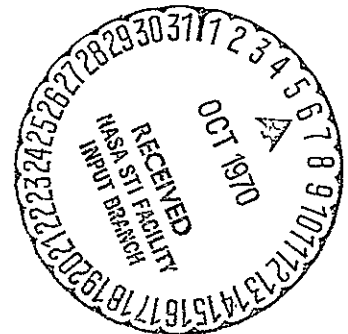
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SURFACE INTERVAL PROVIDING SAFETY
AGAINST DECOMPRESSION SICKNESS IN
HYPERBARIC-HYPOBARIC EXPOSURES:
FINAL REPORT

by

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SURFACE INTERVAL PROVIDING SAFETY AGAINST
 DECOMPRESSION SICKNESS IN HYPERBARIC-HYPOBARIC
 EXPOSURES: FINAL REPORT

ABSTRACT

Astronauts of the Manned Spacecraft Center, Houston, are required to carry out a simulated weightlessness training program at a depth of 40 feet of fresh water at the Marshall Space Flight Center, Huntsville, Alabama. They wear space suits pressurized to 3.5 psi above ambient pressure so that they are exposed to a pressure differential equivalent to 47 feet of seawater.

The underwater program varies, consisting of a single two-hour dive; or two dives lasting two hours each, with a three-hour surface interval between them; or a repetition of the two-dive schedule on a maximum of five successive days, with a minimum of 16 hours separating the work days. Following the underwater exposure, the astronauts then pilot their jet aircraft back to Houston in a flight lasting approximately two hours.

Empirical tests were carried out to determine the probability of an attack of decompression sickness during the proposed compression-decompression training schedule. As a result of the tests, the following surface intervals are recommended before ascent to altitude is attempted following one or more exposures to 47 FSW lasting two hours:

Diving Day	Dive	Surface Interval Between Dives (Hours)		Surface Interval Prior to Ascent to Altitude (Hours)		Maximum Cabin Altitude (Feet)
		Same Day	Different Days	On Air	On Oxygen	
1	1	--	--	1	0	10,000
1	2	3	--	5	0	10,000
1	2	3	--	0	2	10,000
2,3,4,5	1	3	16	3	0	10,000
2,3,4,5	2	3	16	5	0	10,000
2,3,4,5	2	3	16	0	2	10,000
2,3,4,5	2	3	16	3	2	12,000

INTRODUCTION

Astronauts at the NASA Manned Spacecraft Center, Houston, are required to carry out simulated weightlessness training in a tank filled with 40 feet of fresh water (FFW) at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. They wear a standard astronaut's space suit pressurized to 3.5 psi above ambient pressure and so weighted that they are neutrally buoyant. The underwater training program has been designed within the limits recommended in our previous analysis,¹ so that the astronauts make a single dive lasting a maximum of two hours on one day, or two two-hour dives on the same day with a three-hour surface interval between them. This schedule may be repeated perhaps for a maximum of five successive days.

The present study, designed to test empirically the theoretical analysis reported under Contract T-77650, dated 28 March 1969,¹ evaluated the following parameters:

1) The maximum time that the astronauts can safely and effectively work at 47 FSW (which approximates 40 FFW plus a suit pressure of 3.5 psi) without developing decompression sickness after a direct return to the surface.

2) The minimum time that the astronauts must spend at surface pressure, breathing air, after the first dive before a second one of the same depth and duration can safely be undertaken.

3) The safe between-dives surface interval, with air as the breathing mixture, that must separate the second dive of Day 1 and the first dive of Day 2; and the surface interval that must similarly separate all subsequent diving days.

4) The time that must be spent at surface pressure, on an air breathing mixture, after a single 47-FSW dive prior to a flight to Houston lasting two hours.

5) The surface interval required after the second dive of Day 1 prior to ascent to altitude.

6) The surface interval required before it is safe for an astronaut to commence a two-hour flight after the first and second dives of Days 2, 3, 4, or 5.

7) The minimum cabin pressure (maximum cabin altitude) for the two-hour flight that is safe against an attack of decompression sickness following the diving sequences under consideration.

8) The effectiveness of breathing oxygen after multiple dives to shorten the time that must ordinarily be spent breathing air during the surface intervals under consideration.

In all phases of this investigation, special account has been taken of the 680-foot altitude at the MSFC tank site.

ANALYSIS OF DECOMPRESSION SICKNESS

Definitions

Decompression sickness may be defined as those signs or symptoms resulting from decompression carried out at such a rate that gaseous bubbles develop in the body, to such an extent as to cause pain, debilitation, or loss of physiological function. The importance of decompression sickness symptomatology depends upon the area affected and the severity of the symptoms. Decompression sickness can be classified according to whether the symptoms manifest themselves in the central nervous system (CNS), the respiratory system, the joints, or the integumental system. The symptoms--

those involving the CNS, chokes, bends, skin manifestations--may occur during or following the pressure reduction.

CNS manifestations include loss of consciousness, visual disturbances, neurocirculatory shock, paralysis, and paresthesia, all of which result from dysfunctioning of the central and peripheral nervous systems. These symptoms obviously jeopardize the health and welfare of the individual to such an extent that immediate treatment is imperative. However, such manifestations are not considered likely to occur in the pressure-altitude profiles involved in the present investigation and analysis.

Chokes impairs and restricts respiration, and interferes with the normal supply of oxygen to the brain. These symptoms completely incapacitate the individual, and must be treated within a few minutes or the effects may be fatal. Chokes is an uncommon manifestation, and was not expected to occur under the conditions of the present investigation.

Skin manifestations are clinically interesting and subjectively intriguing. These include tingling, formication, numbness, pruritus, rashes, and distortions of temperature sensations. These manifestations would not, however, threaten the completion of a mission or training program such as the one under present consideration.

Bends--the pain whose primary target is the bones and joints--can remain at a barely discernible level, or can develop to such severity that massive doses of morphine might be required to 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 of pressure, or may not become manifest until many hours after pressure has been reduced. With the subject's breathing either air or oxygen,

symptoms may be tolerable and remit with the passage of time at the pressure under which they occur, or they may require recompression therapy.

Within the scope of the pressure profiles under present consideration, the joints one can expect to be primarily affected are the knees and shoulders. Unfortunately, it is not possible to predetermine with any degree of certainty the probable course that bends symptoms will take, once they appear, since so many factors are involved. 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. Bends pains are categorized, according to severity, from 1+ to 4+. The latter is the most severe and is completely debilitating.

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.

Variations in Susceptibility to Decompression Sickness

A maximum reduction in pressure in a diving profile is limited only by the probability that it will cause 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 provide inadequate protection for 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 variations in response to a given pattern of decompression among individual subjects, and also within the same individual. In the latter instance, there is involved the statistical probability that symptoms will develop. There is also the possibility that the minor bodily changes that normally occur from time to time 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 during World War II showed that, as a group, younger men 1) are considerably more resistant to bends at altitude,² and 2) require less preoxygenation time for protection against bends than older crew members do.³

The significant variations in resistance to bends among members of the same age group are possibly attributable 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.² The constitutional factors that appear to render one subject more susceptible to bends than another may, in fact, be simply the difference in the time the tissues of different individuals require to become half saturated with nitrogen. Some factors that may contribute to this difference are obesity, chronic disease, and fatigue.

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 (such as Ar, Kr, Xe, and Ne), as they are normally present in the earth's atmosphere, do not play a significant role in these considerations.

The body responds to an increase or decrease in nitrogen partial pressure (PN_2) in the breathing atmosphere by taking up or eliminating the gas at a rate determined by the specific numerical time constant of each tissue. The amount of gas taken up by the individual tissue is dependent on the PN_2 both in the tissue and in the inspired breathing mixture. The ultimate PN_2 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:

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

in which

P_t = The final partial pressure of nitrogen in the tissues, in feet seawater absolute (FSWA), after an exposure for t minutes;

P_o = The original PN_2 in the tissues, in FSWA, before the exposure to pressure change;

P_a = The PN_2 , 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); and

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 PN_2 , 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 a tissue's half time--i.e., the time required for a tissue to respond to a change in the partial pressure of an inert gas by saturating (or desaturating) to half the gradient formed between the gas in the tissue and in the inspired breathing mixture.

Supersaturation Ratio

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--that is to say, the tissues are in a state of supersaturation. As an example, if a diver's tissues are saturated with a PN_2 of 4 atm, and he is then very rapidly decompressed to 2 atm, the supersaturation ratio between his tissues and the ambient pressure will be 2:1 upon his arrival at a new pressure.

Once supersaturation has occurred within a bodily tissue, the unstable condition will resolve itself in one of two ways: 1) the gas will be eliminated at a rate determined by the tissue's half time and by the gradient formed between the nitrogen in the tissue and in the atmosphere; or 2) a breakdown of the supersaturated solution into stable gas and liquid phases will occur, thus causing gas bubbles to form in the tissues.

Once bubbles have formed, they 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 N_2 supersaturation in a specific tissue.

It was in 1922 that J. B. S. Haldane⁴ advanced his concept that the body is composed of tissue compartments having individual half-saturation times. Based on this theory, the assumption is made that the tissue taking up and eliminating nitrogen the most rapidly has a half-saturation time of five minutes. This tissue will tolerate a supersaturation ratio of approximately 3:1 upon surfacing. (In diving practice, the supersaturation ratio is generally accepted as being the one existing at the time a diver arrives at surface or another new pressure level during decompression.) The slowest tissue--which is the most restrictive one in hyperbaric-hypobaric exposures--is assumed to have a 360-minute nitrogen half time, with a maximum supersaturation ratio upon surfacing of about 1.5:1.⁵

A ratio that can be considered safe against decompression sickness, 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.⁶

The greater the supersaturation ratio is, with respect to a given tissue, the higher the probability 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 safe decompression procedures are unrealistically restrictive. Within specific operational conditions,

therefore, the objective during decompression is to determine a ratio that will be physiologically safe, but not unduly restrictive.

Studies indicate that there may be great differences in the nitrogen uptake and elimination times among individuals,³ and one would expect corresponding individual variations in the maximum safe supersaturation ratios for the slowest tissue as well. But for the purpose of the present investigation, a supersaturation ratio of 1.5:1 for the slowest tissue upon a subject's surfacing has been considered safe for the general diving population.

BASIC ASSUMPTIONS

In analyses of this nature, certain assumptions are necessarily made. First of all, it is assumed that during the 48-hour period immediately prior to the first dive of the series, the subjects have not been exposed to hyperbaric pressure. The inert-gas 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 of any symptoms of decompression sickness for a minimum period of two weeks prior to the first dive, since sites of tissue damage caused by a recent attack of decompression sickness might become focal points for bubble formation upon subsequent decompression.⁷

Marshall Space Flight Center Diving Tank

Virtually all decompression tables in the United States refer to pressure in terms of feet of seawater (FSW). It is therefore expedient to convert all references to pressure units to FSW measurements. One foot of seawater is equal to 1/33rd of the pressure of one atmosphere

(1 atm), or 0.445 psi. One foot of fresh water (FFW) is equal to 1/34th of the pressure of 1 atm, or 0.433 psi.

Since the tank at Marshall Space Flight Center (MSFC) is filled with 40 FFW, it is expedient to calculate its equivalent FSW depth: 40 FFW equals 39 FSW, or 17.32 psi. The astronauts' 3.5-psi suit pressure is equal to approximately 8-FSW pressure, which, when added to the water pressure in the tank, exerts a total pressure on the astronaut that is equivalent to 47 FSW. The elevation at MSFC is approximately 680 ft, which is 0.7 FSW less than 33 FSWA, the equivalent pressure of a standard atmosphere.

The astronauts return to the same surface pressure after their dives that they start from. It is therefore reasonable in the present investigation to designate a differential pressure of 47 FSW as being applicable to the dives, and to base necessary denitrogenation calculations on that pressure.

THEORETICAL ANALYSIS

Because of the hyperbaric exposures to which the astronauts will be subjected in their training schedule at Marshall Space Flight Center, to be followed by their flight to Houston, attention must be directed to the physiological effects on the human organism of the proposed pressure changes. These exposures are such that previous experience and the diving tables in current use do not offer sufficient guidance regarding the appropriate decompression schedules to be followed. We therefore calculated these schedules by using our modification of standard computation techniques, and then validated the results of such calculations by empirical methods.

Nitrogen Tissue Tensions During Hyperbaric Exposure to 47 FSW

To simplify operational procedures of the underwater training program at Huntsville, NASA preferred to restrict pressure exposures to "no-decompression" dive limitations--that is to say, dives to 47 FSW should not be so lengthy that direct ascent to surface cannot be safely made. Direct ascent eliminates the need for the time-consuming procedures of incremental decompression stops and the use of a surface recompression chamber.

The no-decompression depth-time limits as they appear in the U.S. Navy Diving Manual (NAVSHIPS 250-538) are as follows:⁸

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 Fig. 1). Although standard decompression tables in U.S. and U.K. diving manuals are, for the sake of convenience, generally given in multiples of 10 feet, exposure limits for depths between these increments can be estimated.

The depth-time curve shown in Fig. 1 (solid line) demonstrates that a bottom time of 120 minutes can be considered safe for a no-decompression dive to 47 FSW (dashed line), since calculations suggest that a PN_2 in the controlling tissues (those at or near their maximum safe supersaturation

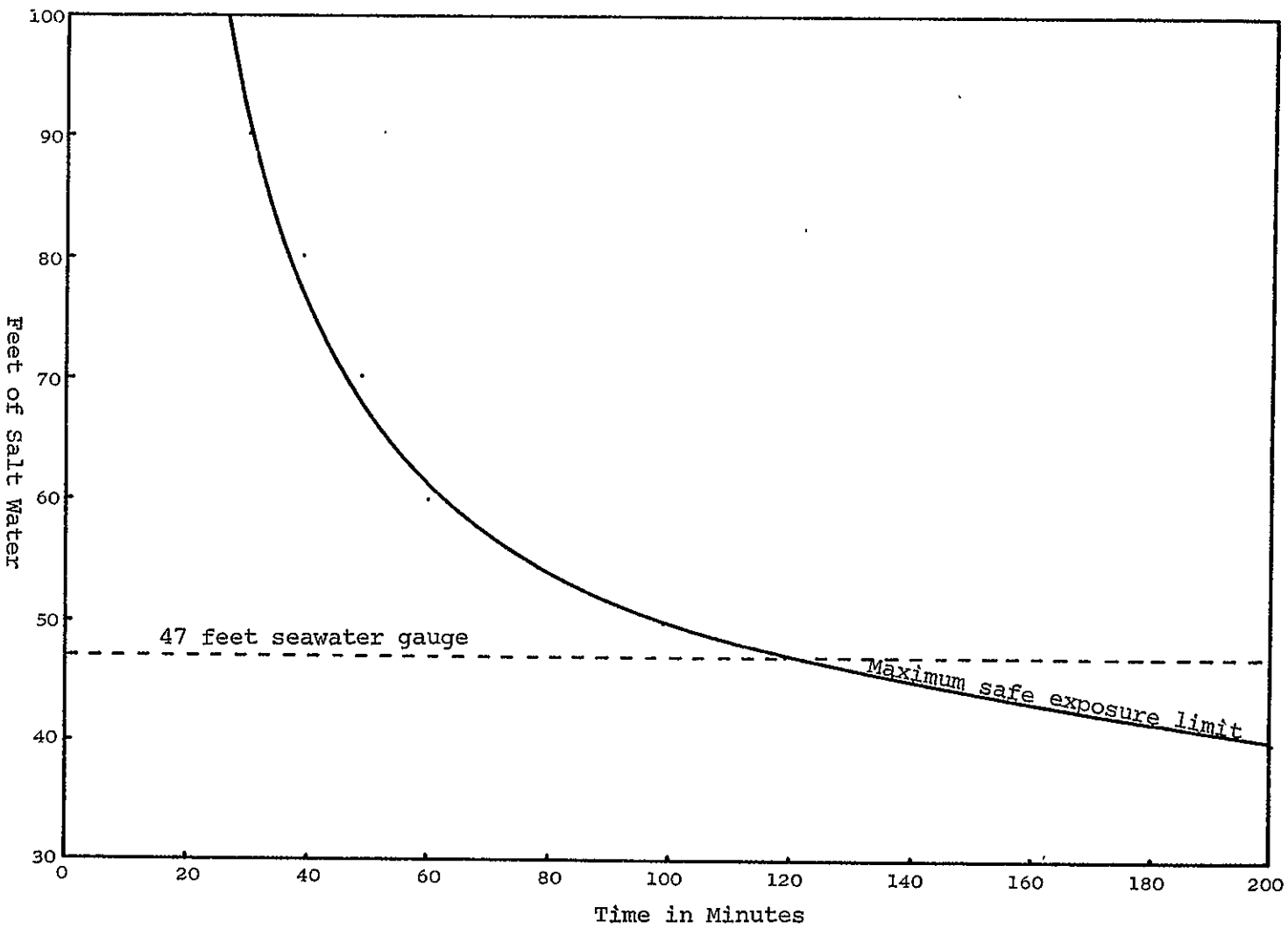


Fig. 1. Curve showing no-decompression diving limitations, in depth and time, when air is the breathing mixture.

ratio, thereby limiting the safe rate of decompression) is about the same in a 47-FSW dive lasting 120 minutes as it is in a 50-FSW dive lasting 100 minutes. Both dives are considered to be well within acceptable safety limits. A maximum work period of 3 hours on the bottom at the MSFC tank would not permit safe direct ascent to surface, and the interval under hyperbaric pressure was accordingly limited to a maximum of 2 hours.

Since the PN_2 in a subject's tissues is assumed to be in equilibrium with the PN_2 in the sea-level atmosphere prior to seawater exposure, his breathing air at a pressure of 1 atm, which equals 33 FSWA, produces a PN_2 in the tissues equal to that of 26-FSWA pressure--i.e., 79% of the total pressure of 1 atm.

Gauge pressure of 47 FSW equals 80 FSWA--i.e., 47 FSW + 33 FSWA (1 atm) equals 80 FSWA. This 80 FSWA multiplied by the 79% N_2 content in the breathing mixture is approximately equal to 64 FSWA ($.79 \times 80$ FSWA = 63.2 FSWA). When a subject breathes air at 47 FSW, he is exposed to a PN_2 of 64 FSWA. And when an astronaut is first immersed in 40 FFW, is wearing a pressure suit inflated to 3.5 psi above ambient pressure, and is breathing air, the PN_2 gradient is 38 FSW--i.e., 64 FSWA (absolute PN_2 in the air at 47 FSW gauge) minus 26 FSWA (PN_2 in the tissues at sea level) equals 38 FSW. The rates of N_2 uptake in the bodily tissues were 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 shown in Fig. 2.

After being under pressure for 2 hours at 47 FSW, the astronaut returns to surface and the PN_2 in his tissues is now greater than that in

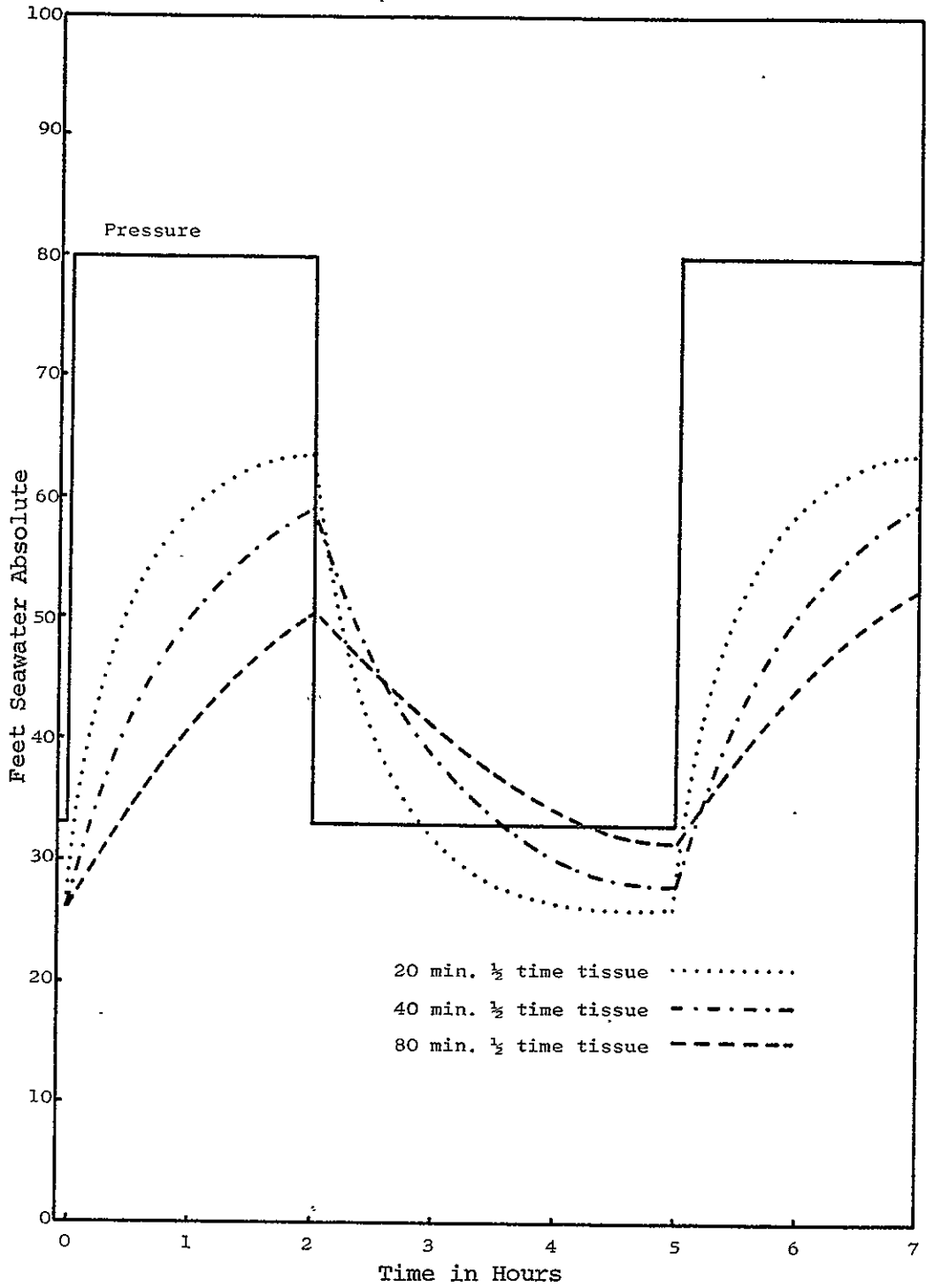


Fig. 2. Partial pressure of nitrogen in 20-, 40-, and 80-minute half-time tissues, showing rate of saturation and desaturation.

the breathing atmosphere, providing an outward gradient for eliminating N_2 from his tissues.

Successive Hyperbaric Exposures

Our computations suggest that after the astronauts make their first 2-hour dive of the series to 47 FSW and are decompressed at the rate of 60 ft/min, the N_2 retention in their slower tissues after 3 hours will not be so great that it must be taken into special account before a second dive comparable to the first is undertaken. That is to say, the residual N_2 retention will not unduly hinder the second recompression.

A second dive may then be undertaken after a given length of time 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 N_2 at the end of the second pressure exposure to be limiting, and the faster tissues will not appreciably have exceeded the N_2 values resulting from the initial exposure (see Fig. 2). In short, it appears safe to make a dive to 47 FSW for 120 minutes with a direct ascent (at the rate of 60 ft/min) to the surface, followed by a surface interval of 3 hours, after which a second dive could be made for the same time and to the same depth as the first one.

As can be seen in Fig. 3 and 4, the 3-hour surface interval has little effect on N_2 elimination from 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 N_2 at the start of the second dive than it did prior to the first one.

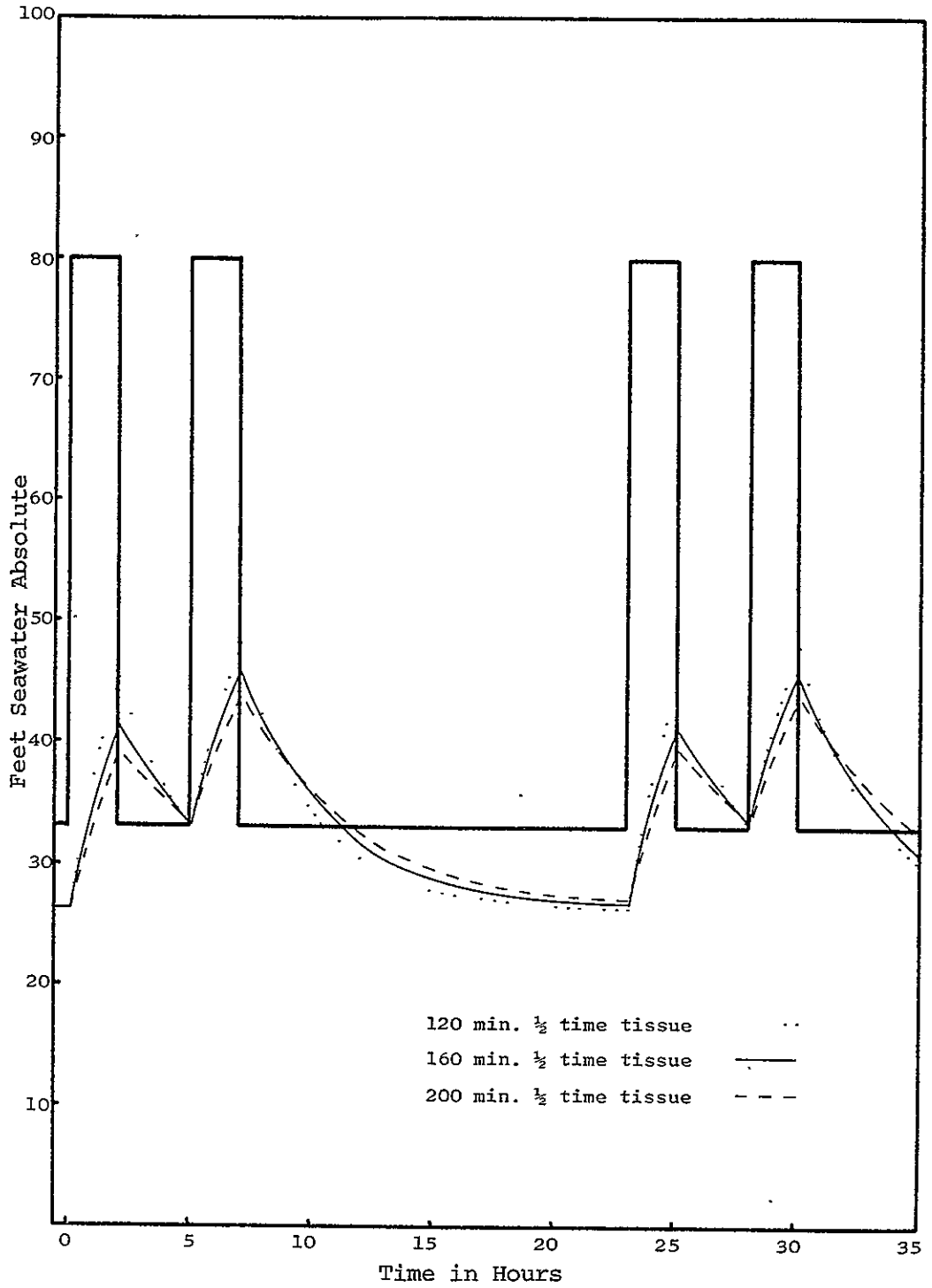


Fig. 3. Partial pressure of nitrogen in 120-, 160-, and 200-minute half-time tissues, showing rate of saturation and desaturation.

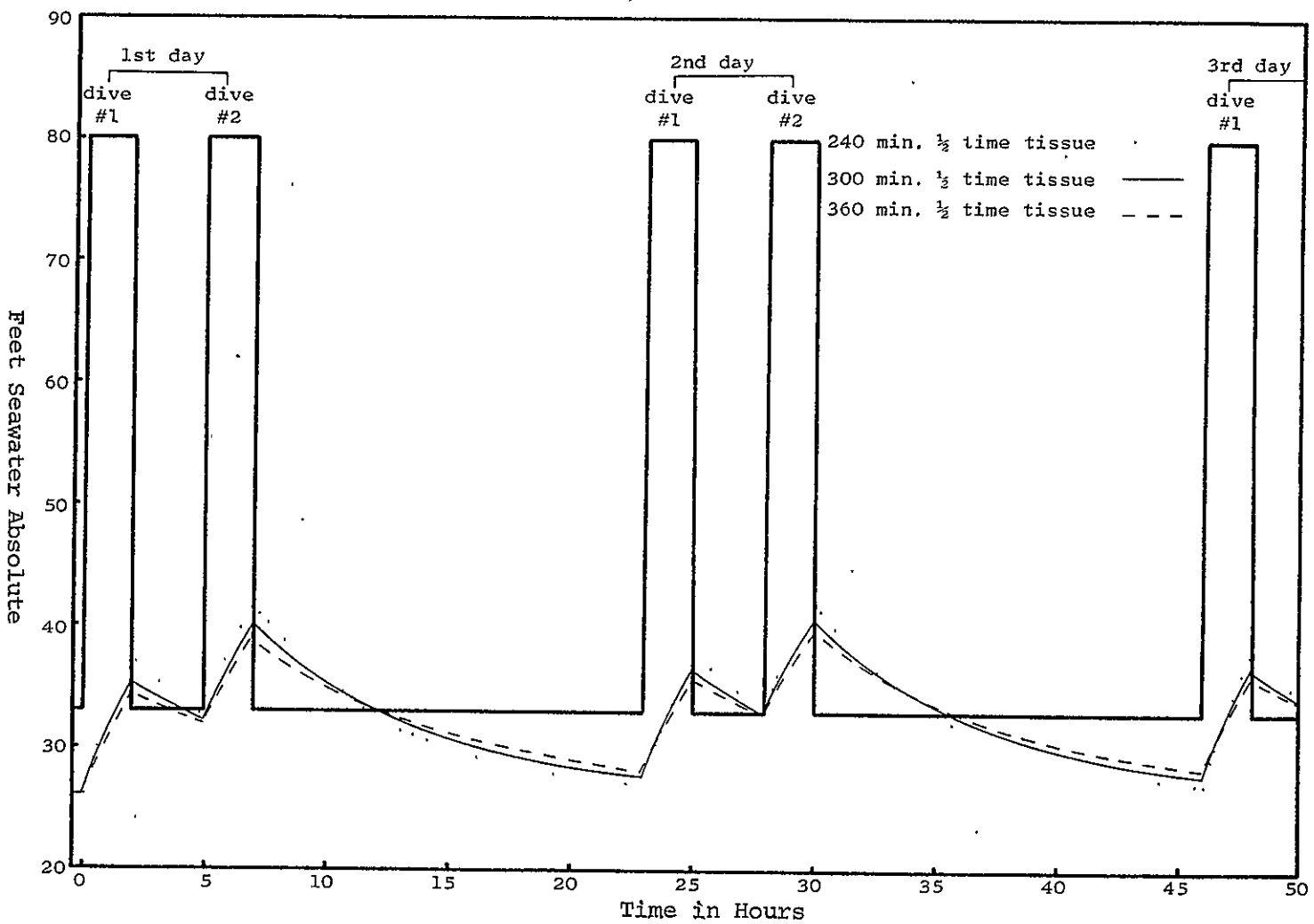


Fig. 4. Partial pressure of nitrogen in 240-, 300-, and 360-minute half-time tissues, showing rate of saturation and desaturation.

If a 16-hour sea-level interval--the logical length of time between one workday and the next--elapses between the second dive of Day 1 and the first of Day 2, some residual N_2 in the tissues accumulated from the first two dives will still be present, according to calculations, when the third dive is made. This accumulation would amount to a 7-1/2% increase in the PN_2 of the slowest tissue at the start of the third dive over the PN_2 existing in the slowest tissue before the first dive. A repetition of the previous day's schedule--that is, two dives to 47 FSW separated by a 3-hour surface interval--following a surface interval of 16 hours would, according to calculations, probably result in a higher PN_2 in the slowest tissue upon surfacing after the two dives of Day 2 (third and fourth dives) than existed after the two dives made on Day 1 (see Fig. 4).

Calculations indicate that further repetition of this same diving schedule would be expected to cause little additional change in the nitrogen tension of the slowest tissues--it would be essentially the same on the third, fourth, and fifth days of diving as it was after the second day. With repetitive diving, the PN_2 in the slowest tissue appears never to attain such magnitude as to prohibit a direct ascent to surface. The slowest tissue would, however, limit the further reduction in pressure of an ascent to altitude following one of the series of dives under consideration.

Hypobaric Exposure Following Hyperbaric Exposure

As stated above, calculations indicate that the nitrogen content of the tissues is still too high following any of the series dives to permit direct ascent to aircraft in-flight altitude without the risk of decompression sickness. During the interval spent at sea level, however,

the tissues begin to denitrogenate and to regain N_2 equilibrium with the sea-level atmosphere. The tissues that took up N_2 the most rapidly will also eliminate it at an equally rapid rate. Conversely, the slower tissues, although they contain much less N_2 than the faster ones do, eliminate it at a slower rate.

Flight crews have not ordinarily been exposed to hyperbaric pressure in the crucial time interval prior to flight, so that the N_2 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 ft (7.75 psia) is eminently safe against decompression sickness, assuming that there has been no recent hyperbaric exposure. The reduction in pressure to 16,500-ft altitude while the P_{N_2} of the bodily tissues is that of 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 a prolonged exposure to 30 feet, during which time air is breathed.

$$30 \text{ FSW} + 33 \text{ FSWA (1 atm)} = 63 \text{ FSWA};$$

$$63 \text{ FSWA} \times 0.79 \text{ (percentage } N_2 \text{ in air)} = 49.8 \text{ FSWA};$$

$$49.8 \text{ FSWA} = N_2 \text{ pressure in tissues after a prolonged dive at 30 FSW};$$

$$49.8 \text{ FSWA} \div 33 \text{ FSWA} = \text{supersaturation ratio of 1.5:1.}$$

In earlier tests⁹ to determine the necessary surface intervals following pressure exposures prior to ascent to altitude, it was noted that the faster tissues with half times of between 10 and 40 minutes attained supersaturation ratios of 2:1 or more upon arrival at an altitude of 8000 ft. The supersaturation ratios in these tissues did not provoke bends.

However, when the 80-minute half-time tissues were involved and the supersaturation ratio was 2:1 on arrival at 8000-ft altitude, mild bends pains were experienced by two of the 10 test subjects.

Since the slower tissues will normally control decompression to altitude following the dives under present consideration (see Fig. 2, 3, and 4), any calculations of schedules may be based on a maximum supersaturation ratio of 1.5:1. Consequently, the minimum safe surface interval prior to ascent to altitude can be calculated simply by applying the 1.5:1 ratio to the tissue containing the highest PN_2 at any given time.

Surface Interval Prior to Flight after Diving

Since the N_2 supersaturation ratio of the tissues is at or near the safe maximum value when the astronaut surfaces, it is obviously not safe for him to undergo a further reduction in pressure until some degree of denitrogenation has taken place. The rate of nitrogen elimination is exponential; it is therefore greatest immediately after a diver surfaces, and the rate progressively decreases 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.

The PN_2 in a diver's slowest tissues is higher when he surfaces after the second and each succeeding dives than it was after the first dive of a series. A separate analysis was therefore made for each dive until the point was reached at which further diving no longer cumulatively increased the load of PN_2 in the slowest tissues; or until the surface interval was sufficiently long to allow the PN_2 in the slowest tissue and in the sea-level atmosphere to attain an approximate state of

equilibrium. Calculations indicated (see Fig. 4) that the PN_2 in the slowest tissues maintains the same values with respect to the pressure profiles during dives of the second day as they do in succeeding days thereafter in the diving program presently under investigation. Calculations also indicated that a 48-hour surface interval is required, following any of the dives under consideration, for the PN_2 in the slowest tissues and in the sea-level atmosphere to regain an approximate state of equilibrium. If the slowest tissue is assumed to have a half time of 360 minutes, eight time constants, or 48 hours ($8 \times 6 \text{ hours} = 48 \text{ hours}$) are required to eliminate 99-1/2% of the excess nitrogen in the tissues. Any dive undertaken after a 48-hour surface interval must therefore be considered Dive 1 of a new series.

Calculations further indicated that after the first 2-hour dive to 47 FSW, ascent to 8000 ft could safely be made following a surface interval of 1-1/2 hours. And ascent to 10,000 ft would be safe following a 2-1/2 hour surface interval.

If a second 2-hour dive is made on Day 1 of the diving program, and a 3-hour surface interval separates the two dives, a minimum 2-1/2 hour surface interval was calculated as safe prior to ascent to 8000 ft, and 4 hours prior to ascent to 10,000 ft.

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 Day 2 of the diving program begins, but will not, however, have returned to a state of equilibrium with the atmosphere (see Fig. 4). After the 16 hours, a third 2-hour dive (the first of Day 2) can safely take place. According to calculations, 2-1/2 hours after this dive is

completed, ascent to 8000 ft can be safely made; or 3 hours after the dive, ascent to 10,000 ft can be attempted without undue threat of decompression sickness.

If a second 2-hour dive is made on Day 2, with an intervening surface interval of 3 hours, the slowest tissue will, upon the second surfacing, attain near-maximum nitrogen tissue-tension values for the series of dives. Calculations indicate that ascent to 8000-ft altitude can be safely made after 3 hours at surface, and ascent to 10,000 ft after 5 hours.

Safe ascent to altitude following the first dive of Day 3, 4, and 5 will require the same surface interval that preceded ascent after the first dive of Day 2. Any second dive made on these days will cause approximately the same N_2 tissue tensions attained after surfacing from the second dive of Day 2. The second dives of the succeeding days will therefore require the same surface interval prior to an ascent to altitude that was required after the second dive of Day 2.

Oxygen Breathing to Reduce the Surface Interval Prior to Ascent to Altitude

Oxygen breathing has been demonstrated to accelerate the rate of nitrogen desaturation from the bodily tissues by producing the maximum obtainable gradient between the PN_2 in the tissues and in the atmosphere. The surface interval between hyperbaric and hypobaric exposures may therefore be significantly reduced through oxygen breathing. For example, our calculations indicated that in the instance of ascent to 10,000 ft following the second dive of Day 2 in a series, the 5-hour surface interval can be reduced to 2 hours if the diver breathes oxygen continuously rather than air.

METHODS

To test the schedules proposed for use in the astronaut training program, a series of experiments was conducted in which the divers were subjected to one of three pressure profiles. The hyperbaric exposures were followed by rapid decompression to surface pressure, and then (following a surface interval to permit denitrogenation) by further decompression to a simulated altitude of 10,000 ft for 2 hours. The tests were conducted in a double-lock hyperbaric pressure chamber of four-ft diameter and a single-lock hypobaric chamber described elsewhere.⁹

In Series A the subjects made a single simulated dive lasting 2 hours to 47-FSW pressure, during which time they breathed chamber air. The dive was followed by an interval at surface pressure varying from one-half to 4 hours before the subjects made a simulated ascent to altitude.

In Series B the subjects made two 2-hour dives to 47 FSW, during which time they also breathed chamber air. The two dives were separated by a 3-hour interval at surface pressure. After the second dive, the subjects spent from 4 to 5 hours at surface prior to being decompressed to simulated altitude.

In Series C the subjects made four 2-hour dives, two on each of two successive days. In each dive they were pressurized to 47 FSW and breathed chamber air. The first two dives were separated by a 3-hour interval at surface pressure. The surface interval between the second and third dives was 15 hours, and the third and fourth dives were separated by a 3-hour surface interval. (See the pressure profiles set out in Fig. 4.)

In all three series, the chamber was pressurized at the rate of approximately 47 FSW per minute, and was depressurized at approximately

half that rate. The subjects in all three series carried out a work program while in the pressure chamber that consisted of lifting a 40-pound weight 1-1/2 ft from the floor at regular intervals for a total of 240 times during the 2-hour period. Following the single pressure exposure in Series A, the second in Series B, and the fourth in Series C, the subjects breathed air, oxygen, or alternately air and oxygen during the surface interval.

Both in the Series A and B experiments, to accelerate the rate of denitrogenation one group of subjects breathed 100% O₂ by mask for the final 2 hours at surface before being decompressed to altitude. Our theoretical analysis had predicted that a surface interval of 2-1/2 hours' air breathing was required in Series A, 4 hours' air breathing in Series B, and 5 hours' air breathing (or 2 hours breathing 100% O₂) in Series C before the astronauts could safely fly at a cabin-pressure altitude of 10,000 ft without a significant probability of incurring decompression sickness. The intervals at surface pressure were varied to test the validity of these predictions, as shown in Table I.

After the fourth dive in Series C, furthermore, the subjects spent a 5-hour surface interval--the maximum surface interval suggested by NASA to follow any dive--and then were depressurized to various altitudes, during which time they breathed alternately air and oxygen. The purpose was to ascertain the maximum altitude pressure that can be safely sustained following the pressure profile used in this series.

The return flight from Huntsville to Houston at the end of the training period was simulated by a hypobaric exposure of 2 hours at an altitude of 10,000 ft (or higher). The rate of ascent was between 5000 and

10,000 ft/min. Following a 2-hour exposure to cabin-pressure altitude in Series C, a short exposure (lasting a maximum of 10 minutes) was made, during which the subjects breathed 100% O₂, to test further the safety of the decompression to altitude. In most of the Series B altitude exposures, and in all of those in Series A and C, exercise was performed. The subjects lifted a 5-pound weight 1-1/2 ft from the floor 240 times during the first 15 minutes of the exposure (see Table I). The purpose was to simulate the added work load that an astronaut might be required to perform during an in-flight emergency. The total work load at simulated altitude was approximately 1/8th of that performed at simulated depth. These relative degrees of effort represent the astronauts training period in the MSFC diving tank and during their homeward flight.

During the hypobaric exposure, the chamber was ventilated with air at 20-minute intervals for 10 minutes to remove CO₂. A normal O₂ and a low CO₂ content in the chamber atmosphere was thus maintained while the subjects breathed O₂ by mask, thereby minimizing the hazard of fire. At simulated altitudes of 10,000 ft or less, air was breathed; and above 15,000 ft, 100% O₂ was breathed continuously. Between 10,000 ft and 15,000 ft, chamber air was breathed when the PO₂ was 110 mm Hg or higher. When the PO₂ fell below this level, the subjects were instructed to breathe from their oxygen masks until the O₂ sensor indicated that the exhaust from the masks enriched the O₂ percentage in the atmosphere sufficiently to bring the PO₂ to some value above 110 mm Hg.

The subjects were observed and questioned regarding signs and symptoms of bends and other forms of decompression sickness, both following the pressure exposure and during the altitude exposure.

TABLE I

*Hypobaric Exposures Following Compression to 47 FSW
and
Exposure to Surface Pressure*

Series	Number of Subjects	Surface Interval after Final Dive		Altitude (Feet)	Work Load at Altitude	Maximum Postflight Altitude Exposure (Feet)
		On Air (Hours)	On Oxygen (Hours)			
A	6	2	2	10,000	+	None
	6	2-1/2	0	10,000	+	None
	4	1/2	0	10,000	+	None
B	2	5	0	10,000	None	None
	2	4	0	10,000	None	None
	2	4	0	10,000	+	None
	10	2	2	10,000	+	None
C	4	5	0	10,000	+	20,000
	4	0	2	10,000	+	20,000
	4	3	2	12,000	+	25,000
	4	3	2	15,000	+	25,000
	2*	0	0	--	--	--

*Test aborted after second dive of Day 1 because of attack of bends in one subject at surface

RESULTS

Series A. The 16 subjects in this series were given a single pressure exposure to 47 FSW and worked, as was said, both under hyperbaric and hypobaric conditions. None experienced any signs or symptoms of decompression sickness, either during the surface interval or the simulated altitude exposure that followed. The results of the tests are shown in Table II.

TABLE II

Tabulation of Results of Experiments in Series A

Number of Subjects	Surface Interval (Hours)		Subjects Experiencing Decompression Sickness	
	On Air	On Oxygen	After Dive	During Altitude Exposure
6	2	2	0	0
6	2-1/2	0	0	0
4	1/2	0	0	0

Series B. In this series 16 subjects underwent two exposures to 47 FSW separated by a 3-hour surface period. The results are shown in Table III.

Two subjects were involved in each of the first two experiments of Series B. In the first, the subjects were exposed to a 5-hour surface interval following the second dive, and in the second, a 4-hour surface interval, before exposure to the simulated 10,000-ft altitude. In neither experiment did the subjects experience any signs or symptoms of decompression sickness; neither, however, was any work performed during the simulated altitude exposure.

TABLE III

Tabulation of Results of Experiments in Series B

Number of Subjects	Subjects with Decompression Sickness after First Dive	First Surface Interval (Hours)	Subjects with Decompression Sickness after Second Dive	Second Surface Interval		Subjects with Decompression Sickness at Altitude (10,000-Ft)
				On Air (Hours)	On Oxygen (Hours)	
2	0	3	0	5	0	0*
2	0	3	0	4	0	0*
2	0	3	0	4	0	2
10	0	3	0	2	2	0

*No work was performed during the 2-hour period at altitude

In the third experiment of Series B, also involving two subjects, there was a 4-hour surface interval following the second dive. A work schedule was carried out during the first 15 minutes of the altitude exposure. Within 30 minutes of reaching simulated altitude, both subjects, who had been free of symptoms up to that point, developed bends. One had pain in the knees, while the other experienced pain in the shoulder. Within 10 minutes of the onset of symptoms, both subjects reported that the pain was so severe (4+) that they could not continue the test. The chamber was depressurized, and both subjects were symptom-free by the time they reached surface pressure. The symptoms did not recur.

In the fourth group of experiments in Series B, which involved 10 subjects, air was breathed for the first 2 hours of the 4-hour surface interval, and 100% O₂ was breathed by mask during the second 2 hours. None of the subjects experienced any signs or symptoms of decompression sickness, either after their exposures to 47 FSW or during their exposure to the simulated altitude of 10,000 ft, despite the work schedule performed both under hyperbaric and hypobaric conditions.

Series C. In this series there were 18 subjects, 16 of whom underwent four 2-hour exposures at 47 FSW, two dives being made on one day and two the next (see Tables IV and V). In the first experiment of the series, two subjects completed a morning and an afternoon dive on the same day. One subject noticed pain in his right elbow 8 hours after surfacing from the second dive, the pain progressing to between 2+ and 3+ within the next 7 hours. He was therefore recompressed to 60 FSW. During 20 minutes at that depth, during which time he breathed O₂, he experienced only slight relief. The subject was then further compressed, to 165 FSW, and was switched to air breathing; at that pressure he reported complete relief

of pain. Twenty minutes after compression to 165 FSW began, he was, within 5 minutes, decompressed to 60 FSW and treatment was completed in accordance with U.S. Navy Treatment Table 6a. He suffered no recurrence of symptoms. The other subject remained symptom-free, but could not continue with the experiment because of his partner's attack of decompression sickness. None of the other 16 subjects in Series C experienced any symptoms at surface pressure and they continued with the two-day experimentation.

In the second experiment of Series C, four subjects were involved. After the afternoon dive of Day 2 the subjects, breathing air, remained at surface pressure for a period of 5 hours. They then were exposed to an altitude pressure of 10,000 ft for 2 hours, followed by a further pressure reduction to 20,000-ft altitude for a maximum of 10 minutes.

The four subjects experienced no symptoms during the exposure at 10,000 ft. One felt a slight discomfort in his right knee during the decompression from 10,000 ft, which became 3+ pain at 17,500 ft. At this latter altitude a second subject noticed 1+ symptoms in both shoulders. Recompression to surface pressure was started within one minute of these subjects' arrival at 17,500 ft, all symptoms completely remitting during their simulated descent. Neither of the other two subjects experienced any discomfort at any point during the ascent to 20,000-ft altitude pressure, or during the 10-minute exposure there.

In the third experiment of Series C, four subjects were involved. Following the afternoon dive of Day 2, they remained at surface pressure for a period of 2 hours and breathed oxygen. Following the surface interval they were exposed to an altitude pressure of 10,000 ft for 2 hours, followed by a further reduction in pressure to 20,000 ft for a maximum of 10 minutes. None of the subjects experienced any symptoms at 10,000

ft, and three of them remained symptom-free at 20,000 ft. The fourth subject, however, noticed pain in his right knee at 20,000 ft, which increased to 3+ severity during the 10 minutes spent at that altitude. As in the second experiment of the series, the symptoms completely remitted during recompression to surface, and did not recur.

Four subjects were involved in the fourth experiment of Series C. Following the afternoon dive of Day 2, the subjects remained at surface pressure for 5 hours, during which time air was breathed for 3 hours and oxygen for 2. They were then exposed to an altitude pressure of 12,000 ft for 2 hours, followed by a further reduction in pressure to 25,000 ft for a maximum of 10 minutes. None of the subjects had any symptoms of decompression sickness at 12,000 ft, and three of the four remained symptom-free during their 10-minute stay at 25,000 ft. One subject had symptoms in his right thigh shortly after arrival at 25,000 ft, the pain progressing to 3+ in the 10 minutes spent at that altitude. His symptoms regressed completely during the recompression to surface pressure.

Four subjects were involved in the fifth and final experiment in this series. Following the afternoon dive of Day 2, the subjects breathed air at surface pressure for 3 hours and then oxygen for 2. After this surface interval they were exposed to an altitude pressure of 15,000 ft for a 2-hour period, after which they were to be exposed for 10 minutes at 25,000 ft.

One subject experienced 1+ pain in his right knee upon arrival at 15,000 ft. It increased to 2+ within 30 minutes, but regressed to 0 over the next 90 minutes at this pressure. The pain recurred during decompression to 18,000 ft and became 3+ upon arrival at 20,000 ft.

TABLE IV

Tabulation of Results of Experiments During Hyperbaric Exposure in Series C

Test	Number of Subjects	Bends Incidence after First Dive	First Surface Interval (Hours)	Bends Incidence after Second Dive	Second Surface Interval (Hours)	Bends Incidence after Third Dive	Third Surface Interval (Hours)	Bends Incidence after Fourth Dive
C-1	2	0	3	1	--	--	--	--
C-2	4	0	3	0	15	0	3	0
C-3	4	0	3	0	15	0	3	0
C-4	4	0	3	0	15	0	3	0
C-5	4	0	3	0	15	0	3	0

TABLE V

Tabulation of Results of Experiments During Hypobaric Exposure in Series C

Test	Number of Subjects	Surface Interval after Fourth Dive (Hours)		Simulated Flight Altitude (Feet)	Time Spent at Flight Altitude (Minutes)	Bends Incidence at Flight Altitude	Maximum Altitude (Feet)*	Bends Incidence at Maximum Altitude Exposure
		On Air	On Oxygen					
C-2	4	5	0	10,000	120	0	20,000	2
C-3	4	0	2	10,000	120	0	20,000	1
C-4	4	3	2	12,000	120	0	25,000	1
C-5	4	3	2	15,000	120	3	25,000	1

*Time scheduled to be spent at maximum altitude in each test: 10 minutes

The second subject had no symptoms at 15,000 ft, but developed 1+ pain during decompression to 20,000 ft, at which point the experiment was aborted to accommodate both Subjects 1 and 2.

The third subject in this fifth experiment of Series C had 1+ pain in both knees upon arrival at 15,000-ft altitude. After 5 minutes the pain in his right knee had progressed to 2+, but gradually diminished to 0 during the rest of his stay at that pressure. During the first 90 minutes at 15,000 ft, the pain in his left knee progressed to 2-1/2+ and remained at that intensity for the rest of the simulated flight. The subject was brought to surface after the 2-hour exposure at 15,000 ft.

The fourth subject in the experiment reported 1+ pain in his right thigh upon arrival at 15,000 ft. Intensity increased to 2+ during the first hour at that pressure and did not regress during the rest of the 2-hour exposure. At that point he was brought to surface pressure to accommodate his teammate, Subject 3, after which he was decompressed to 25,000 ft. His symptoms recurred at 20,000 ft, became 2+ at 25,000 ft, and progressed to 3+ within one minute at the latter altitude, whereupon the test was terminated. As in the previous tests in this series, all subjects reported complete remission of symptoms during the recompression to sea-level pressure, after which the symptoms did not recur.

DISCUSSION

Maximum Length of Single Exposure to 47 FSW

In the single 2-hour exposures to 47 FSW, followed by a direct return to surface pressure, a total of 66 man-exposures was involved: 16 in Series A, 16 in Series B, and 34 in Series C. The surface interval following the first dive of Day 1 was 3 hours in Series B and C, and varied from 5 to 0.5 hours in Series A. According to standard diving practices, a surface interval of 12 hours would be required to ensure the majority of the diving population against an attack of decompression sickness after any single dive. However, the fact that none occurred after the 3-hour surface interval in these tests suggests that 3 hours is sufficient to provide a high probability of safety. Furthermore, the minimum surface interval tested--30 minutes--prior to the subjects' ascent to 10,000-ft pressure, at which altitude they remained for 2 hours without incidence, indicates that a single dive to 47 FSW lasting 2 hours is eminently safe. A hypobaric exposure after so short a time at surface would otherwise be expected to increase the growth of bubbles formed following a single hyperbaric exposure (see Table I).

Hypobaric Exposure Following a Single Dive to 47 FSW

Our theoretical analysis of the problem of exposure to 47 FSW, followed by a decompression to altitude pressure, predicted that a 2-1/2 hour surface interval between the pressure exposure and ascent to altitude would be necessary to protect the astronauts against decompression sickness. On the basis of six man-exposures, this surface interval appears to be safe. As we pointed out, furthermore, four additional man-exposures in which the surface interval was only 30 minutes also proved safe.

Thirty minutes after the astronaut surfaces from a single 2-hour 47-FSW exposure, the PN_2 in his 40- and 80-minute half-time tissues has been lowered sufficiently (see Fig. 2) so that the supersaturation ratio is approximately 1.9:1 when he later reaches 10,000-ft altitude. This ratio appears safe for the 80-minute tissues at this altitude, and it is more than adequate for the 40-minute tissues. The supersaturation ratios of the slower tissues--120-minute tissue, 1.85:1; 160-minute tissue 1.75:1; 200-minute tissue, 1.65:1--also appear safe, although marginally so, for resting subjects at this altitude (see Fig. 3).

The demonstrated safety of the 30-minute surface interval is consistent with the results of a similar study⁹ designed to determine the minimum safe surface interval between a hyperbaric exposure to 40 FSW lasting 2 hours. No symptoms of decompression sickness occurred in the six subjects given the 30-minute surface interval. However, when the surface interval was further reduced to 5 minutes, two of the 12 subjects experienced decompression sickness. In these studies, relatively high (in excess of 1.5:1) nitrogen supersaturation ratios were also reached in the 80- to 200-minute tissues upon ascent to altitude.

It is significant that in the 40- and 47-FSW experiments, the supersaturation ratios, although higher than 1.5:1, were safe--especially in view of the fact that the subjects exercised during the first 15 minutes at altitude in the 47-FSW test. The safety of a 30-minute interval following a single 2-hour 47-FSW exposure, prior to ascent to 10,000-ft altitude, might well be questioned for persons having a greater-than-average susceptibility to decompression sickness. A one-hour surface interval, however, would be adequate for the astronauts prior to their homeward flight if they maintain a true cabin altitude of no more than 10,000 ft.

Minimum Safe Surface Interval between Morning and Afternoon Dives and between Two Dives on Different Days

After the astronauts surface from a 2-hour dive to 47 FSW, their tissues will contain sufficient excess nitrogen to prevent their immediately making a second such dive without the serious risk of decompression sickness after surfacing from the second dive. No tests were done in the present experimentation specifically to determine the minimum surface interval that must separate the two dives. From an operational standpoint, however, 2 to 3 hours are needed after the first dive to enable the astronauts to dress, debrief, have lunch, and then get suited for the second dive. Our computations indicated that 3 hours is a minimum safe surface interval between two such dives, and 3 hours was therefore selected.

In Series B and C, there were 50 man-exposures in which there were two dives to 47 FSW separated by a 3-hour surface interval. Eight hours after surfacing from the second dive, one subject suffered an attack of decompression sickness of such severity that recompression was required to effect relief. The incidence of decompression sickness resulting from the two-dive profile, in which the surface interval was 3 hours, was therefore 2%, suggesting that the time spent at surface should not be reduced.

The 2% incidence would seem to constitute an acceptable risk, especially since all the factors known to contribute to the occurrence of decompression sickness--e.g., maximum pressure exposure to 47 FSW, minimum surface intervals, maximum time of exposure to depth, and a high work rate under pressure exposure--would rarely in actual practice be expected to combine in any repetitive -dive series. When the depth, time, or work load of either dive in a repetitive series is less than those of our test conditions, or the surface interval is longer than 3 hours, the probability of the occurrence of decompression sickness decreases.

The 16-hour surface interval between the second dive of any day and the first dive of the following day was also largely determined by operational expediency--1600 hours on one day until 0800 hours on the next being logically the end of one work day and the beginning of another. A 15-hour surface interval was tested in 16 man-exposures with no incidence of decompression sickness, thereby validating the 16-hour interval.

Effects of Exercise

Concerning Series B, in which those subjects who exercised following the hyperbaric-hypobaric exposure sequence developed bends, whereas those who did not work remained symptom-free: It has long been recognized that strenuous exercise after a pressure reduction that produces marginally safe N_2 supersaturation in the tissues will promote sufficient bubble formation to cause decompression sickness. On the other hand the same decompression profile with the same reduction of pressure, but without exercise, will probably not provoke symptoms. Furthermore, in those exposures in which a given pressure reduction can be expected to produce a certain incidence of decompression sickness, the incidence will be greatly increased when moderate or heavy work is performed.¹⁰

These investigators also demonstrated in some studies that the number of cases of decompression sickness following a given reduction in pressure was more than doubled when there was a moderately heavy work load at altitude, in comparison with the number occurring when the subjects merely rested. In these studies, the subjects' work loads were more or less evenly distributed throughout their stay at the reduced pressure level. The effects of work performed at irregular intervals, rather than being distributed during the entire hypobaric exposure, have been given little or no attention to date.

Since the level of tissue supersaturation is normally greatest immediately upon a subject's undergoing a pressure reduction, one can expect his tissues at that time to be the most vulnerable to bubble formation. Therefore, exercise performed immediately after a pressure reduction should have its greatest effect in triggering an attack of decompression sickness. Scheduling the work program in the third of the Series B experiments for the first 15 minutes after arrival at the 10,000-ft altitude pressure thereby created the optimum conditions for an attack. The work output during the first 15 minutes of the ascent to altitude pressure was assumed to approximate that of an in-flight emergency occurring within the first 15 minutes of an actual flight.

Since the N_2 supersaturation ratio gradually decreases as N_2 is eliminated following decompression, the detrimental effect of exercise dissipates steadily with the passage of time. Exercise has little or no effect by the time the PN_2 in the tissues and that in the breathing medium are in equilibrium, or are close to it. If all the work is done in a given segment of time just after the pressure reduction, rather than being performed at regular intervals during the exposure, one can expect a higher incidence of decompression sickness than if the work were done at the end of the exposure.

To offset the effects of the work to be performed at altitude pressure, the last 2 hours of the 4-hour surface interval in the fourth experiment of Series B was spent breathing 100% oxygen. This period allowed sufficient denitrogenation of the tissues so that a safe supersaturation ratio existed when the 10,000-ft altitude pressure was reached. The 10 subjects remained symptom-free.

Hypobaric Exposure Following Repetitive Diving

Although a higher nitrogen tension in the slowest tissues is attained after Day 2 (or thereafter) of series dives, in comparison with that of Day 1, it does not limit decompression to surface pressure. The higher P_{N_2} does, however, limit further decompression to altitude pressure. Day 2 requires a longer surface interval following two hyperbaric exposures than Day 1 does, so that the slowest tissues have sufficient time to denitrogenate to safe levels before further decompression to altitude is attempted.

We predicted in our earlier analysis¹ that 5 hours of air breathing would be required before a subject could safely ascend to a 10,000-ft cabin altitude pressure following the hyperbaric exposures of Day 2. Four subjects in Series C accordingly spent 5 hours at surface pressure before ascending to that altitude for 2 hours. To determine if 10,000 ft represents the maximum altitude that can be tolerated in these circumstances, the subjects were then further decompressed to 20,000 ft. They remained at the latter altitude for 10 minutes, sufficient time for any "silent" bubbles that might have formed at 10,000 ft to proliferate and cause symptoms.

Of the four subjects thus exposed, two (or 50%) developed decompression sickness. Following the two hyperbaric exposures of Day 2 (or of any day thereafter) and a 5-hour surface interval during which air is breathed, ascent to cabin pressures greater than 10,000 ft appears to incur an unacceptable risk of decompression sickness.

Since nitrogen tensions after the two hyperbaric exposures of Day 1 are lower than they are on Day 2, exposure sequences deemed safe after Day 2 are even more so after Day 1.

Oxygen Breathing to Reduce the Surface Interval

The surface interval preceding the astronauts' homeward flight from Huntsville following the second dive of Day 2 (or any day thereafter) is crucial in that it determines the altitude at which the flight may be safely made. (Once more, any interval deemed safe after Day 2 is even more so after Day 1.) For operational expediency, it was decided that diving on any day be completed no later than 5 p.m., and that the astronauts leave for Houston no later than 10 p.m.

In these 5 hours, the astronauts will become sufficiently denitrogenated on air breathing to ascend to 10,000-ft altitude, as we have stated. However, the introduction of oxygen breathing, or alternating oxygen with air breathing, accomplishes one of two purposes: It will shorten the surface interval prior to ascent to a maximum of 10,000-ft altitude; or, leaving the surface interval at 5 hours, it will raise the maximum altitude to which the astronauts may ascend.

Our test results show that 2 hours of O_2 breathing at surface affords the same protection against decompression sickness that 5 hours of air breathing does. Or, said another way, under these circumstances N_2 is eliminated 2-1/2 times faster with O_2 than it is with air breathing. It is not always practical or possible for a diver to begin O_2 breathing immediately after a hyperbaric exposure; neither can he always breathe O_2 continuously for 2 hours. Since denitrogenation of the slowest tissues begins immediately when the subject reaches surface and begins air breathing (although at a slower rate than when O_2 is breathed), O_2 breathing may be started any time following the dive. It may also be interrupted without adverse effect, as long as a total of 2 hours of cumulative O_2 breathing precedes ascent to a maximum cabin pressure of 10,000 ft.

The maximum rate of N_2 elimination from the tissues can be accomplished by a diver's beginning O_2 breathing immediately after he surfaces from the series dives under consideration. However, immediate and continuous O_2 breathing, which must be done by mask, is not always feasible or desirable (breathing by mask fast becoming irksome, among other considerations). A combination of air and oxygen breathing therefore becomes desirable, if not necessary.

As can be seen in the mathematical model of nitrogen uptake and elimination in the *BASIC ASSUMPTIONS* section of this report, and from Fig. 2, 3, and 4, the N_2 elimination rate is greatest when air is breathed immediately after a diver reaches surface pressure following a dive and is then followed by O_2 breathing. Since it is not always possible to begin O_2 breathing immediately upon termination of a dive, the following rules can be used to accommodate oxygen-air breathing after the afternoon dive of Day 1, or after any subsequent dive, in a repetitive series prior to flying:

1) For every 2-1/2 minutes that a subject spends breathing air *before* beginning O_2 breathing, one minute can be subtracted from the required 120 minutes of O_2 breathing;

2) If O_2 breathing is interrupted, it should be resumed until the cumulative O_2 exposure equals the total time of O_2 breathing set out in rule 1) above, or until the surface interval totals 5 hours.

3) The period of air breathing will decrease the period of oxygen breathing *only when air inhalation precedes oxygen inhalation.*

Example: Let us say that on Day 2 of a repetitive series a subject surfaced after the second 2-hour dive to 47 FSW and breathed air for 50 minutes before beginning O_2 breathing. The 120-minute period of surface

O₂ breathing before ascent to 10,000-ft cabin pressure could thereby be reduced by 20 minutes (50 minutes ÷ 2-1/2), leaving 100 minutes on O₂. Let us further assume that after 50 minutes of O₂ breathing there was a 15-minute interruption during which air was breathed, after which O₂ breathing was resumed without further interruption. The total surface interval prior to flight would thereby become 165 minutes, calculated as shown in Table VI. (See also Fig. 5).

TABLE VI

Example Showing Method of Computing Oxygen-Breathing Interval after Interval of Air Breathing at Surface

Time Sequence	Breathing Medium	Oxygen Breathing Time Equivalent
From 1st to 50th min	Air	20 min
From 50th to 100th min	Oxygen	50 min
From 100th to 115th min	Air	0 min
From 115th to 165th min	Oxygen	50 min
Total: 165 minutes		Total: 120 minutes

Since 5 hours (or 300 minutes) is the necessary surface interval prior to flight to 10,000 ft when air is the sole breathing medium, a partial substitution of O₂ breathing thus would cut 135 minutes from the surface interval.

As the rate of N₂ elimination from the tissues is greatest immediately after surfacing, and progressively decreases thereafter, O₂ breathing will be the most effective in the latter part of a surface interval. Greatest effectiveness should therefore be achieved by the

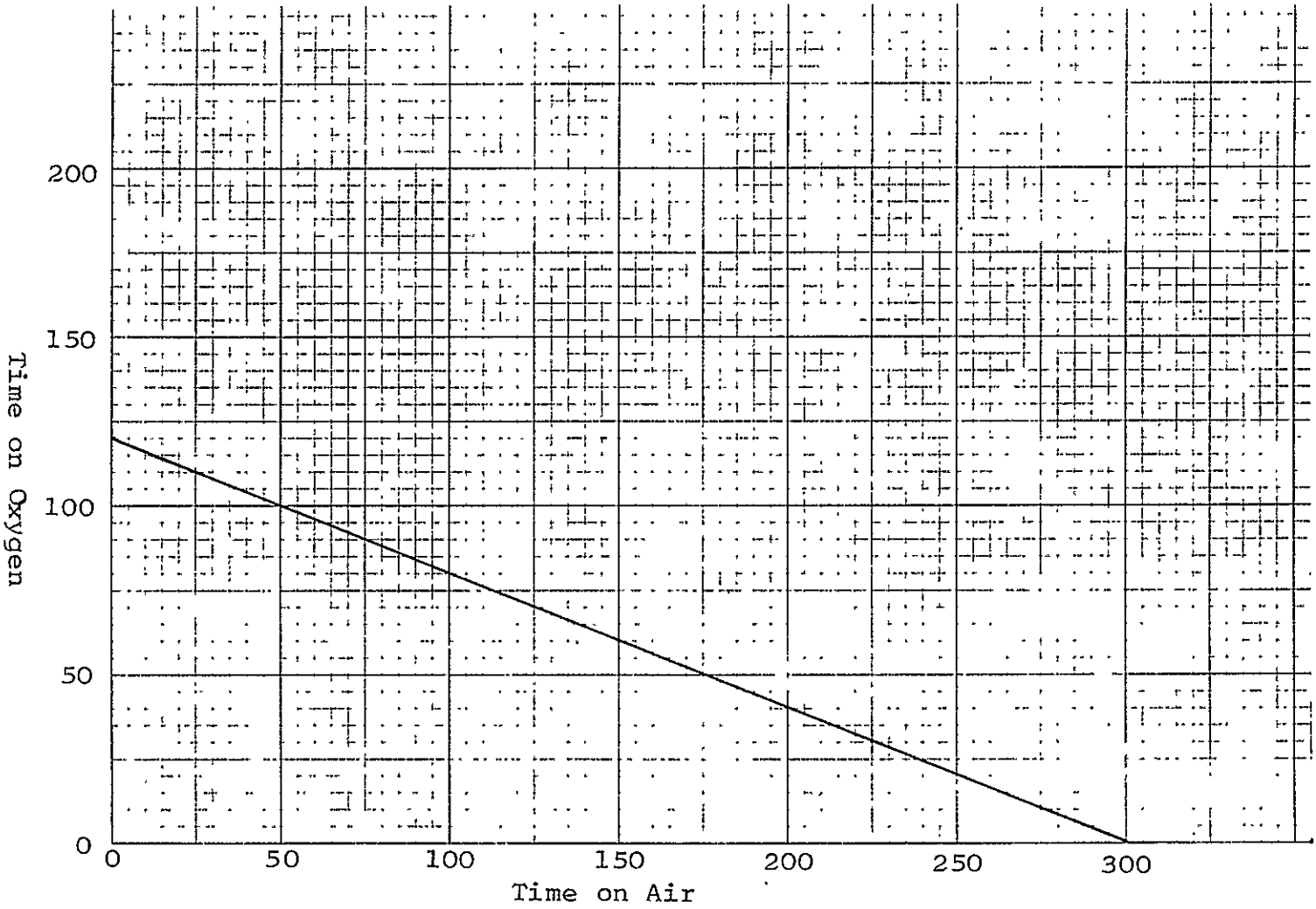


Fig. 5. Graphic presentation demonstrating air-oxygen rule for determining surface interval.

astronauts' first breathing air for 3 hours and then 100% O₂ for 2 hours prior to ascent to an altitude above 10,000 ft.

Maximum Safe Altitude Pressure Following Repetitive Hyperbaric Exposures

We next proceeded to determine the maximum safe altitude to which the astronauts might ascend following the afternoon dive of Day 2 and a surface interval not to exceed 5 hours.

In the third experiment of Series C, oxygen was breathed for 2 hours following this dive prior to the subjects' ascent to 10,000-ft altitude pressure. There was no incidence of decompression sickness. The subjects then were further decompressed to 20,000 ft for 10 minutes. One of the four, or 25% of the subject population, suffered symptoms at the greater altitude. This hyperbaric exposure profile, followed by a 2-hour surface interval during which O₂ is breathed, must therefore be considered insufficient protection against decompression sickness at altitudes greater than 10,000 ft.

In the fourth experiment of Series C, four subjects, following the second dive of Day 2, remained on surface breathing air for 3 hours and O₂ for 2. They then ascended to an altitude of 12,000 ft and remained at that pressure for 2 hours. None of them experienced any symptoms of decompression sickness. The subjects were then exposed to 25,000-ft pressure for 10 minutes, and only one of them suffered any symptoms.

These results stand in marked contrast to those of the final experiment in Series C. The exposures and surface intervals in this fifth experiment were identical to those of the fourth, except that in the latter the subjects were exposed to a simulated pressure altitude of 15,000 ft. During two hours at that pressure, three of the four subjects

suffered attacks of bends; and when, after 2 hours, pressure was further reduced to 25,000 ft, the remaining subject suffered an attack.

It would therefore appear that following a surface interval of 5 hours after the afternoon dive of Day 2 (or of any day thereafter) the maximum altitude that can be tolerated is 10,000 ft when air only is the breathing medium, but that the period can be cut to 2 hours with pure-oxygen breathing. When air is breathed for 3 hours and oxygen for 2, the maximum altitude that can be tolerated is 12,000 ft.

Surface Interval after Each Dive of Day 2 Prior to Hypobaric Exposure

Although no tests were conducted to determine the required surface interval after the 2-hour morning dive to 47 FSW on Day 2 (or any day thereafter), the basic profile should be more conservative than the surface interval tested for the first dive of Day 1. It would thereafter appear reasonable to adopt a 3-hour surface interval prior to ascent to a 10,000-ft cabin pressure, as suggested by calculations in an earlier analysis.

A complete listing of the required intervals prior to an ascent to altitude is given in Table VII.

TABLE VII

Surface Intervals Required Prior to an Ascent to Altitude

Diving Day	Dive	Surface Interval Prior to Ascent to Altitude		Cabin Pressure Altitude (Feet)
		On Air (Hours)	On Oxygen (Hours)	
1	1st	1	0	10,000
1	2nd	5	0	10,000
1	2nd	0	2	10,000
2,3,4,5	1st	3	0	10,000
2,3,4,5	2nd	5	0	10,000
2,3,4,5	2nd	0	2	10,000
2,3,4,5	2nd	3	2	12,000

It is important to note the progress of symptoms in the two subjects who suffered an attack of decompression sickness at altitude in the third experiment of Series B. The subjects first noted the symptoms after 30 minutes at the 10,000-ft altitude, and within 10 minutes the pain had become so great that the test had to be aborted. Since in practice a return to sea-level cabin pressure within 10 minutes is not possible, every effort should be made to avoid conditions favoring the formation of nitrogen bubbles. The necessity for strict adherence to the outlined decompression requirements and procedures cannot be overemphasized, as they are vital to the health and well-being of the personnel involved.

Variations or Loss of Cabin Pressure: Emergency Procedures

The schedules proposed herein are based upon in-flight pressures to which the astronauts will be exposed following a dive or series of dives. Completion of such a flight without incidence of decompression sickness will depend in part upon accurate control of cabin pressure. If the 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 will increase.

In commercial passenger flights the cabin pressure is maintained at an altitude of 8000 ft 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 (Air Force regulation AF62-3645, for example, allows a variation of ± 1000 -ft cabin-pressure setting at 8000 ft), possible fluctuation must be taken into account. The aircraft cabin altitude selected must be at least 1000 ft less than the maximum altitude specified for a given surface interval.

Should cockpit pressurization fail, yet be restored within a minute or so, it is extremely unlikely that decompression sickness will result. This is particularly true toward the end of a 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--e.g., 20,000 ft for 5 minutes--than the one indicated in the schedules set out in Table V (particularly at the beginning of the flight), decompression sickness is a probable consequence. Hence efforts should

be directed toward effecting a return to surface as soon as possible to forefend such a possibility.

If definite symptoms of decompression sickness are noted during a flight, the only hope of relief is a return to sea-level pressure as rapidly as possible. The pilot should, as quickly as possible, reduce the aircraft's altitude to the lowest one consistent with flight safety. In the types of military aircraft currently being used by the astronauts, the cabin pressure is equal to the ambient pressure at altitudes less than 8000 ft, meaning that the aircraft would have to be flown as close to the ground as possible in an attempt to effect some degree of temporary relief. In addition to increased cabin pressure, breathing 100% oxygen may be helpful in relief of symptoms. Although the use of pure oxygen should be encouraged if symptoms of decompression sickness arise, oxygen alone cannot be expected to produce a significant degree of relief.

CONCLUSIONS

1. An astronaut can be exposed at the bottom of a 40-foot tank while wearing a pressure suit inflated to 3.5 psi (total pressure, 47 FSW) for a period of 2 hours, and then return directly to the surface without incurring a significant probability of developing decompression sickness.

2. If the astronaut breathes air at surface pressure for 3 hours or more after a 2-hour dive at 47 FSW, he can then safely repeat the dive.

3. After the second of two such dives on a single day, a surface interval of 16 hours is necessary, during which air is breathed, before the astronaut can safely make another 2-hour dive to 47 FSW.

4. A daily schedule of two dives to 47 FSW for 2 hours, the first dive to be followed by a surface interval of 3 hours and the second, 16 hours, may be safely repeated on an indefinite number of days.

5. Ascent to an absolute cabin altitude of 10,000 feet for 2 hours can be safely made one hour after completion of a single dive to 47 FSW that lasts not more than 2 hours.

6. If a third dive is made to 47 FSW for 2 hours (following a surface interval of not less than 16 hours after surfacing from the second dive), a flight may then be safely made to an absolute cabin altitude of 10,000 feet after a 3-hour surface interval during which air is breathed.

7. Following a second 2-hour dive to 47 FSW on the first day (or any day thereafter), the two dives on one day having been separated by a 3-hour surface interval, a flight may be safely made to 10,000-ft absolute cabin altitude for 2 hours. The surface interval following the second dive of the day may be either 5 hours during which air is breathed, or

2 hours, during which time 100% oxygen is breathed, or a combination of air and oxygen breathing.

8. In the pressure profile outlined above, if a period of air breathing on surface precedes breathing 100% oxygen breathing, the total obligated oxygen-breathing time may be decreased by one minute of oxygen breathing for each 2-1/2 minutes spent breathing air.

9. If interrupted during the surface interval, oxygen breathing should be continued until the cumulative total is 2 hours before the subject ascends to 10,000-ft altitude, the total time at surface not to exceed 5 hours.

10. Following an afternoon dive on any day of the series diving to a depth of 47 FSW for 2 hours, a flight to 12,000 feet may be safely made after a 3-hour surface interval during which air is breathed followed by a 2-hour period of oxygen breathing.

11. Because of the severity of symptoms and the rapidity of their development, at the first definite sign of decompression sickness the aircraft should be flown to the lowest possible altitude consistent with flight safety.

12. When symptoms of decompression sickness are first noticed in flight, the stricken person should breathe pure oxygen and continue to do so until surface pressure is reached. Oxygen breathing should be maintained at the surface until the symptoms subside.

13. In view of the specified tolerances in the cabin pressure control system of the aircraft presently used by the astronauts, it is recommended that these decompression procedures be applied to an indicated cabin pressure setting of 1000 feet less than that specified in Table VII.

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