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PREDICTING THE POSSIBILITY
OF
DECOMPRESSION SICKNESS, OR BENDS, IN
MANNED ORBITAL FLIGHTS

by

Peter O. Edel

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J & J Marine Diving Company, Inc.
Pasadena, Texas
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ABSTRACT

Astronauts undergoing decompression to orbital cabin pressure are subjected to the dissolution of gases from their bodily tissues in proportion to the decrease in partial pressure of these gases, thus incurring the possible consequence of decompression sickness. In calculating a safe level of supersaturation of inert gas--in this instance, nitrogen--in the bodily tissue, techniques used in diving table computations were adapted for use in similar computations of pressure changes occurring in orbital flight. From these computations, the following hypothesis was developed: in order to prevent the occurrence of bends in orbital flight, the ratio of nitrogen partial pressure (within those bodily tissues having the slowest elimination rate) to the ambient pressure should not exceed 1.5:1. Graphs are herein submitted that predict a safe decompression rate according to the degree of nitrogen elimination that has been achieved. No advantage exists in the substitution of any other inert gas for nitrogen in the breathing atmosphere. Results of experiments that were conducted to test the validity of the recommended decompression procedures in the interval prior to extravehicular activity are presented herein.

INTRODUCTION

The possibility that members of an astronaut crew will develop decompression sickness at orbital altitudes is a classic problem in aerospace medicine. Operational mission rules for Mercury and Gemini flights have always taken into account the contingency of bends, and have included specific directions to be followed in the event of decompression sickness. The further decrease in atmospheric pressure occurring when the capsule is decompressed prior to extravehicular activity (EVA) only aggravates the threat. That the Apollo and future space flight systems involve the possible use of breathing mixtures containing an inert gas in addition to oxygen makes the possibility of decompression sickness an even greater hazard. The present investigation, then, was undertaken in an effort to evaluate the problem of the decompression sickness that occurs (1) after decompression to capsule pressure during orbital flight, and (2) after further decompression to the "space suit" pressure of EVA at 3.5 psia.

The same techniques and computations used to determine the level of toleration of inert gas supersaturation in bodily tissues in diving environments were adapted to determine similar levels of tolerance to bends in aviation and space environments.

ACKNOWLEDGMENTS

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P. O. E.

DECOMPRESSION SICKNESS

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. In general, CNS decompression sickness is debilitating, and would jeopardize the health and welfare of the afflicted astronaut to such an extent that immediate termination of the mission would be required. However, CNS symptoms are not considered likely in the type of pressure-time profiles to which astronauts are subjected.

"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.

"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 relieve the pain. The symptoms can develop with extreme rapidity, or gradually increase in intensity over a period of many hours. They may occur during the actual reduction in pressure, or may not manifest themselves until many hours after pressure has been reduced. Symptoms may be tolerable and remit spontaneously with either the passage of time or oxygen breathing. Most often, however, they do not remit, which would require premature termination of the mission should they occur during orbital flight.

In the instance of bends, it is not possible to predetermine with any degree of certainty the probable course of symptoms, 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 type of pressure-time profiles applicable to a space flight mission, bends are the most probable. The prime targets of attack are the knees and shoulders. Knee bends are the most likely of all bend symptoms to require a premature termination of the mission, and shoulder bends are the most likely to remit spontaneously.

Skin manifestations are clinically interesting and subjectively intriguing. They would not, however, threaten the normal completion of an orbital mission.

That bends occur in a small percentage of military and commercial diving experiences is of no great concern. However, if astronauts were to experience decompression sickness during a space flight, the entire mission would be placed in jeopardy.

The following calculations were carried out to determine which procedures--both prior to and during the flight--with respect to pressure-time profiles and breathing media, produce the lowest bends probability in space crews.

THE THEORY OF NITROGEN UPTAKE AND ELIMINATION IN THE BODILY TISSUES

Of the several inert gases contained in the earth's breathing atmosphere, the only one of special significance in the study of decompression sickness is nitrogen. The effects of oxygen and carbon dioxide (and the rare gases, krypton, xenon, argon in the concentrations present in the earth's atmosphere) do not play a significant role in these considerations. The tissues respond to an increased or decreased partial pressure of nitrogen by taking up or eliminating nitrogen at a rate determined by the time constant of the tissue in question, and the gradient formed between the nitrogen partial pressure in the tissue and the partial pressure of nitrogen in the inspired breathing mixture. The value for the partial pressure of nitrogen in a bodily tissue for a specific time interval, after a change in the partial pressure of nitrogen, is expressed by the following equation:

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

P_t: The final tissue partial pressure in psia of nitrogen after an exposure of t minutes.

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

P_a: Partial pressure in psia of nitrogen in the breathing medium during the exposure.

e : Base of natural logarithms.

t : Time of exposure in minutes.

k : $\frac{0.693}{T\frac{1}{2}}$ (tissue time constant).

$T\frac{1}{2}$: Tissue half-saturation time in minutes.

0.693: Logarithm to the base of e of 2.

The rate at which the tissue responds to a partial pressure gradient 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. The rate is more commonly indicated by referring to 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 point in several minutes, whereas a "slow" tissue may take several hours to achieve it.

The rate of response in terms of arbitrary half-time units is shown in Figure #1. Curve A represents a condition wherein the bodily tissue is saturated to a given level (as in the case of an astronaut prior to preoxygenation) and then responds to a breathing mixture in which there is no nitrogen--i.e., P_a=0. At the end of one half-time period, 50% of the nitrogen is eliminated and the driving force (P_a-P_o) is likewise reduced by one-half. After a second period of time equal to the initial half-time interval, the tissue partial pressure is reduced to 50% of the value existing at the start of the time interval, or to 25% of the initial value. Each successive half-time interval will reduce by one-half the tissue tension existing at the beginning of that interval. As curve A illustrates, the process of total tissue tension reduction is never really

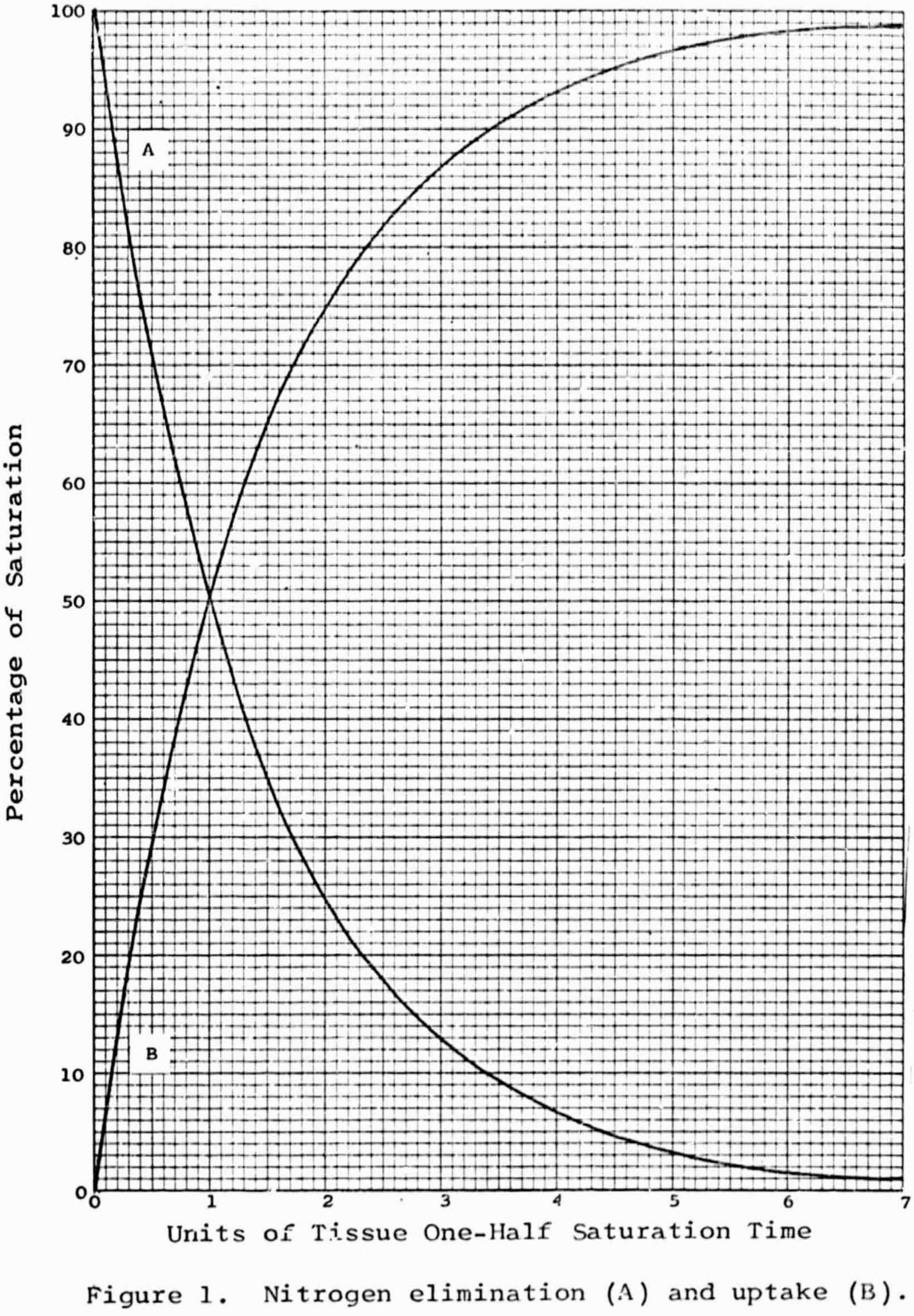

Figure 1. Nitrogen elimination (A) and uptake (B).

completed, but is reasonably approximated within five to ten of these half-time intervals.

The reverse of this process is illustrated in curve B, which plots the rate of nitrogen uptake of a tissue that is initially devoid of nitrogen, and then is exposed to a given partial pressure of nitrogen in the inspired breathing mixture.

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 the partial pressure of nitrogen. 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 the partial pressure of nitrogen in the breathing mixture and in the tissues.

If, as illustrated by curve A in Figure 1, a specific half time of 5 minutes is assigned to correspond with an accepted value for the fastest tissue, after 30 minutes about 98½% of the nitrogen the tissue initially contained has been eliminated. If a tissue has a half-saturation time of 60 minutes, 6 hours are required to reach that value. At the point a 5-minute half-time tissue has lost 98½% of the nitrogen it formerly contained, the 60-minute tissue still retains more than 70% of its initial nitrogen load. A tissue with a half time of 300 minutes would, after one hour, still retain over 87% of the gas initially dissolved in the tissue.

Under normal circumstances, the partial pressure of nitrogen in the air is considered to be in equilibrium with the partial pressure of nitrogen in the bodily tissues at sea level. The following conclusions can be drawn from the foregoing rates of elimination in different half-time tissues: starting from a condition of equilibrium, the body tissue that is the slowest in taking up and eliminating inert gas (hereafter called the slowest tissue) will always contain a nitrogen tissue tension equal to or greater than that of any other bodily tissue when the inspired nitrogen partial pressure has, for one reason or another, been lowered and sustained at a reduced level. This condition is representative of the partial-pressure profiles that apply to the astronauts just prior to and during the ascent, as well as during the space flight itself.

THE USE OF THE RATIO OF PARTIAL PRESSURE OF NITROGEN IN THE BODILY TISSUES TO AMBIENT PRESSURE IN PREDICTING THE OCCURRENCE OF DECOMPRESSION SICKNESS

A stable condition exists when the nitrogen tissue partial pressure is at equilibrium with the partial pressure of nitrogen in the inspired breathing mixture, assuming that nitrogen is the only inert gas present in such a mixture. The bodily tissues are then completely saturated. During decompression, the concern is with a state wherein the pressure has been reduced to such a level that the nitrogen in the tissues is in excess of the normal level of saturation for pressure and temperature--that is to say, the tissues are in a state of supersaturation. Once a state of supersaturation has been attained within a bodily tissue, the unstable condition may 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) breakdown of the supersaturated solution into stable gas and liquid phases will occur, thus forming gas bubbles in the tissues.

In the latter instance, the 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. Supersaturation may be expressed as the ratio of the partial pressure of nitrogen in the bodily tissues to the ambient pressure. Thus if a diver is saturated to a nitrogen partial pressure of four atmospheres and then is very rapidly decompressed to two atmospheres, the supersaturation ratio would be 2:1 upon his arrival at the new pressure depth.

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. The greater this ratio is, the higher the probability that bubble formation and decompression sickness will result. If, on the other hand, the ratio is too conservative, the gradient (P_a-P_o) formed for further elimination of inert gas (nitrogen) becomes so small that the decompression procedures become unrealistically restrictive. The objective is to determine a ratio that will be physiologically safe, but not unduly restrictive, during decompression within the specific operational conditions.

In aerospace situations, all tissues of the body are considered to be saturated at sea level pressure prior to decompression to altitude. Following a period of equilibrium in all bodily tissues, if partial pressure in the breathing mixture is constantly maintained throughout decompression at a level less than that of the partial pressure in the slowest tissue, the progress of decompression is limited by that tissue. The slowest tissue is, therefore, the only one to be considered in predicting the probability of decompression sickness, and in programming orbital missions in order to prevent or minimize an attack of bends.

Since the quantity of nitrogen in the slowest tissue is very small in comparison with the relatively large quantities of nitrogen in the faster tissues, present-day techniques of measurement have proved inadequate to the task of determining accurately the uptake and elimination times for the slowest tissue. Nevertheless, schedules for safe decompression after total saturation exposure on Sea Lab I and II were proven to be eminently safe for the vast majority of personnel exposed.

In the Sea Lab schedules, inert atmospheres were based upon gas exchange following an exponential curve with a half-saturation time of 240 minutes. Other decompression schedules, based upon the slowest tissue as the controlling factor and a half-saturation time of 240 to 360 minutes, have been successful in chamber and open-water tests in which the slowest tissue was the limiting one for all or a portion of the schedule.

The maximum supersaturation ratio in the slowest tissue that can be tolerated in the return to sea level from a higher pressure has been well demonstrated both in carefully controlled tests and under normal operating conditions. The United States Navy conducted experiments with subjects who were brought to sea level after prolonged exposure to elevated pressure, and has adopted a value of 22¼ psia partial pressure of nitrogen in the slowest tissues at the moment of surfacing[1]. This value is equivalent to an individual's returning to sea level after an indefinite stay at a 30-foot water depth, at which time the ratio 22¼ (nitrogen tissue tension upon surfacing) to 14.7 (absolute pressure at sea level) is slightly in excess of 1.5:1.

In the decompression of aviators from sea level pressure to the pressure at altitude, experience in altitude chamber tests and in flight has shown that a rapid ascent to 16,500 feet is eminently safe. The partial pressure of nitrogen in bodily tissues at sea level is equal to the percentage of nitrogen in air (79.1%) multiplied by the atmospheric absolute pressure at sea level (14.7 psia). The nitrogen partial pressure in the tissues is, therefore, 11.6 psia at sea level (.791 x 14.7=11.63 psia). A reduction in absolute pressure to 16,500 feet altitude, or 7.75 psia, represents a supersaturation ratio of 1.5:1 (11.63/1.5 psia= 7.75 psia). An ascent to this altitude from sea level is considered in current aeromedical practice to be eminently safe, insofar as the danger of an attack of bends is concerned.

In rare instances, bends have occurred upon ascent to altitudes slightly higher than 16,500 feet. Subjects who are highly resistant to bends can, of course, sustain tissue supersaturation ratios greatly in excess of the average; and direct ascent, lasting several hours, to altitudes in excess of 35,000 feet have occasionally been made without incidence of decompression sickness[2].

There are, to be sure, those extremely rare individuals who appear to be uniquely susceptible to bends, and who defy virtually all attempts to program completely safe decompression schedules. Applying the hypothetical nitrogen supersaturation ratio of 1.5:1 to tissues having a 360-minute one-half saturation time has proved safe in all but a very few instances. Furthermore, this ratio provides an extremely generous margin of safety when applied within these depth-altitude limits.

APPLICATION OF SUPERSATURATION RATIO TO 360-MINUTE HALF-TIME TISSUE IN DECOMPRESSION PROCEDURES FOR SPACE FLIGHTS

When the body is at sea level, the tissue tension of nitrogen is 79.1% of 14.7 psia, which is approximately equal to a tissue partial pressure of nitrogen of 11.63 psia. With this partial pressure, the limiting supersaturation ratio of 1.5:1 should permit a maximum pressure reduction to 7.75 psia, or 16,500 feet altitude. Denitrogenation by means of breathing oxygen prior to flight has been used to reduce this nitrogen level in the slowest tissue. The rate of denitrogenation occurs in approximately the manner shown in Figure 2. After 3¼ hours of oxygen breathing at sea-level pressure, the nitrogen level will then be about 8.4 psia, which, applying the above ratio, would permit a pressure reduction to 5.6 psia.

When further denitrogenation has reduced the nitrogen partial pressure in the tissues to 5.25 psia, the ratio then applied indicates that exposure to a pressure of 3.5 psia is a safe one for EVA. This reduction in tissue partial pressure of nitrogen can be accomplished either by means of a longer period of oxygen breathing prior to flight, or by breathing nitrogen-oxygen mixtures or oxygen alone at orbital pressures, as shown in Figures 3 and 4.

In using nitrogen-oxygen mixtures at orbital altitude, the combined reduction in the percentage of nitrogen in the cabin atmosphere and in the cabin pressure to 5.6 psia (compared with 14.7 psia at sea level) results in a very low partial pressure of nitrogen in the alveolus of the lungs. This low pressure creates a high gradient of pressure within the body, which accelerates the elimination of residual nitrogen from the slowest tissues.

On the other hand, the nitrogen partial pressure will present an inward gradient, resulting in the uptake of nitrogen in the faster half-time tissues in which nitrogen tissue tension has been decreased to a level below that of cabin atmosphere during the process of preoxygenation. However, with a 50%N_2-50%O_2 cabin atmosphere, the nitrogen partial pressure is at a level far lower than one considered safe for the slowest tissue in EVA.

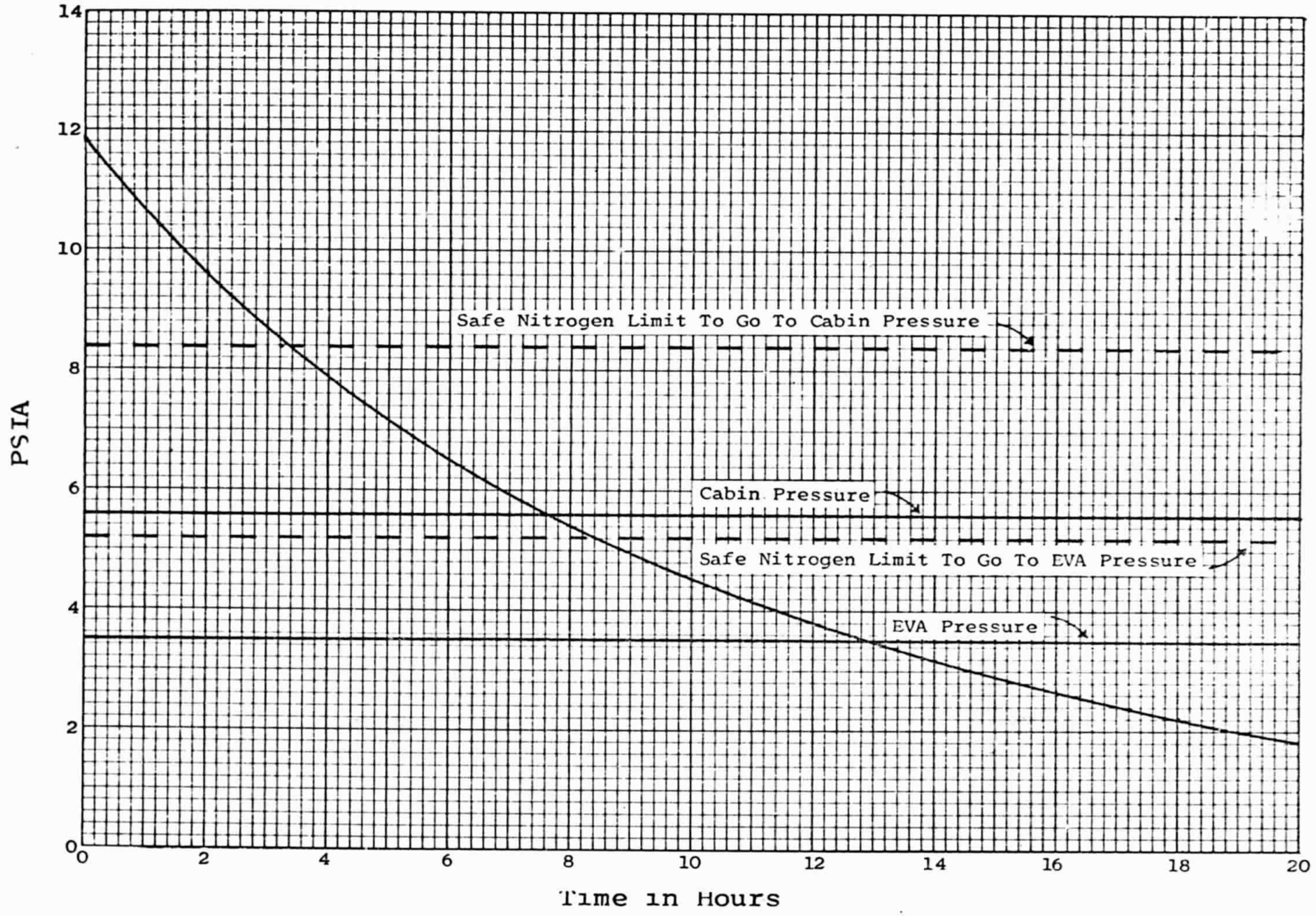

Figure 2. Nitrogen elimination curve for slowest tissue during oxygen inhalation.

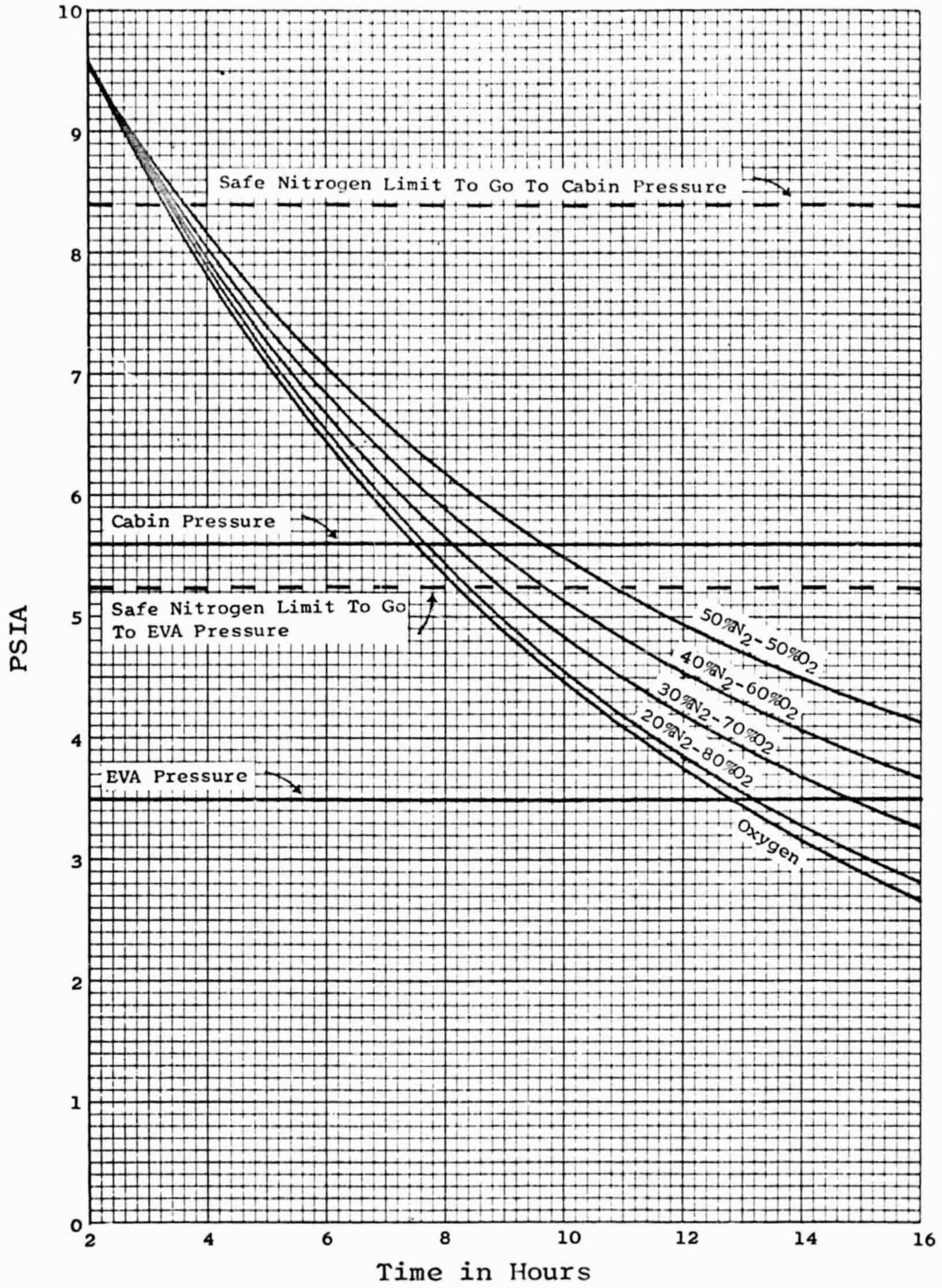

Figure 3. Nitrogen elimination curve for slowest tissue during inhalation of various gas mixtures at cabin pressure of 5.6 psia following two hours of preoxygenation.

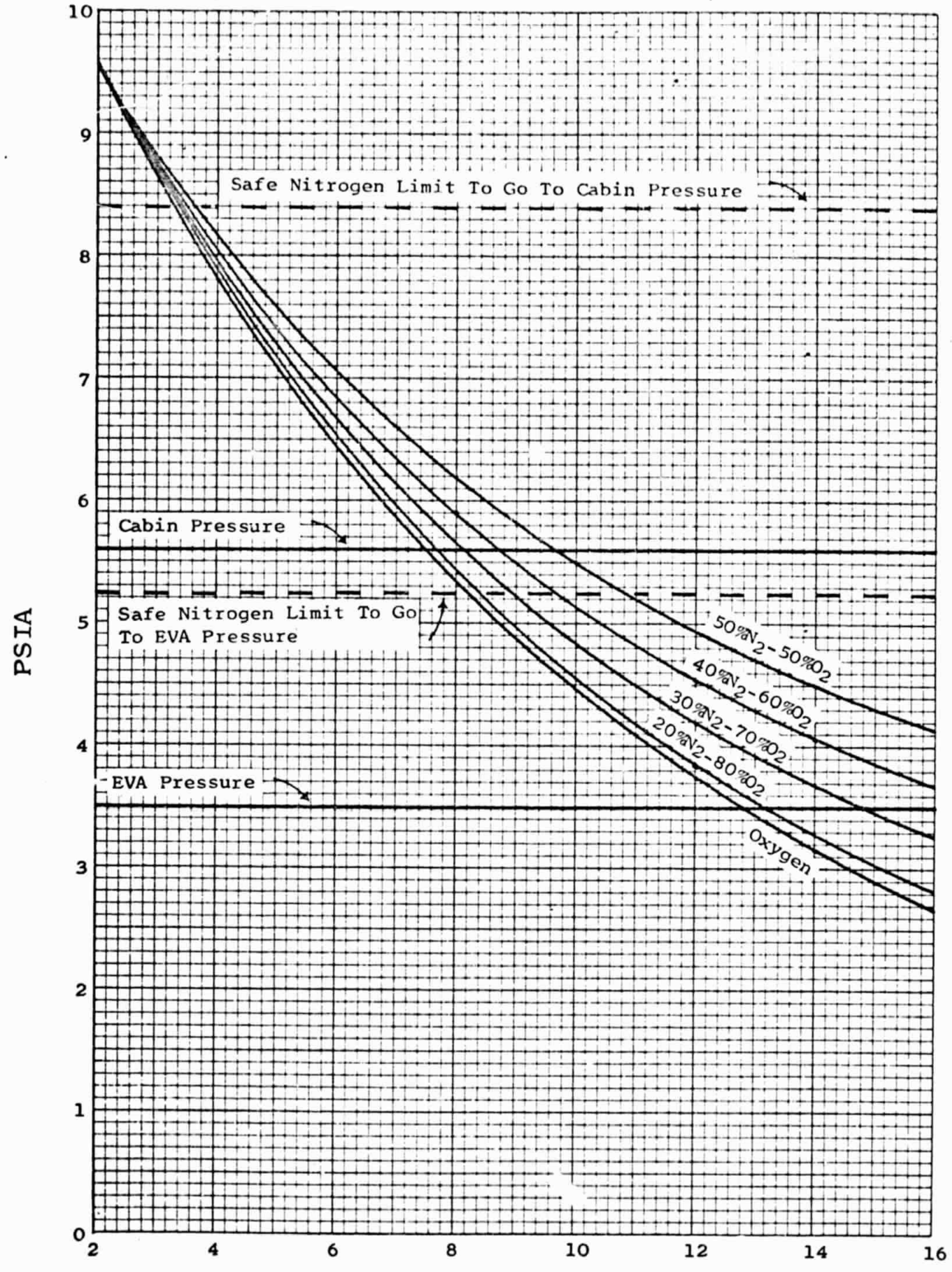

Figure 4. Nitrogen elimination curve for slowest tissue during inhalation of other gas mixtures at cabin pressure of 5.6 psia following two hours of preoxygenation.

With a capsule pressure of 5.6 psia, the nitrogen partial pressure is (for a 50%N_2-50%O_2 mixture) .5 x 5.6=2.8 psia, which is, in fact, less than orbital suit pressure during EVA. Therefore, nitrogen saturation of the faster tissues resulting from breathing a 50%N_2-50%O_2 mixture at orbital altitude is not of concern. Obviously, mixtures containing higher oxygen percentages would reduce even further the saturation limitations of the faster tissues at orbital pressures.

Experience has demonstrated that a supersaturation ratio providing safety against bends in continuous ascent, or in multiple stage decompression, can be greatly exceeded if a single decrease in pressure occurs. Furthermore, a similar supersaturation ratio can be tolerated in multistage decompression procedures if the time intervals between pressure decreases are greatly prolonged[3]. Excessive changes in pressure appear to create a condition in the tissues closely approximating decompression sickness, but without sufficient severity to produce symptoms. However, this physical condition must be resolved before pressure can be further reduced without incurring the danger of bends.

During space flights, such factors as an accidental loss of pressure may cause a supersaturation ratio in the astronauts' tissues that is far in excess of the suggested safe limits, yet does not produce immediate symptoms of decompression sickness. However, bubbles may form in the tissues that will produce symptoms at a later time, or that will remain unnoticed until they become expanded by a later reduction in pressure.

Under the foregoing conditions, the gas elimination curves cannot be relied upon to predict adequately the rate of removal from the tissues. Safety considerations, therefore, demand that no further decrease in pressure take place for 24 hours following a return to a pressure level within the 1.5:1 ratio, so that sufficient time is allowed for the redissolution of possible bubble formation.

A METHOD OF DETERMINING TISSUE TENSION AND ALLOWABLE SUPERSATURATION OF NITROGEN IN THE SLOWEST BODY TISSUE

Provided that the 1.5:1 ratio is not exceeded in EVA or during an unscheduled reduction of cabin pressure, an attack of decompression sickness can be prevented through a simple series of calculations made from Figures 2,3,4, and 5 (nitrogen uptake and elimination curves).

Nitrogen is eliminated from the body tissue, in accordance with the time schedule set forth in Figure 2, during the period of preoxygenation. The exponential decay curve for the critical tissue produces a corresponding increase in the gradient formed by the difference between the nitrogen tissue tension and the partial pressure of nitrogen at sea level. If a break occurs in the preoxygenation schedule, the effects are twofold. Time is, of course, lost from the preflight preparation schedule; and nitrogen tissue tension increases because of the greater nitrogen partial pressure in the breathing medium. The effects on the astronauts, however, are insignificant if the time lost does not exceed a few minutes.

In order to determine the effect of a break in the preoxygenation schedule upon the process of denitrogenation, this hypothesis is used: the nitrogen tissue tension level from Figure 2, at the time the break occurs, is subtracted from the value taken for the partial pressure of nitrogen at sea level (11.63 psia). The remainder is then multiplied by the factor $1-e^{-kt}$ obtained from Figure 5 with respect to the length of time air was breathed. The product obtained is added to the tissue tension value at the time preoxygenation was interrupted. When oxygen breathing is resumed, preoxygenation time is then plotted from the new value.

These calculations may be used as many times as necessary to determine the effect of additional breaks in the preoxygenation schedules. When the nitrogen tissue tension has reached the value of 8.4 psia, as represented by the upper broken line in Figure 2, safe ascent to cabin pressure of 5.6 psia is indicated. However, the tissue tension must be further reduced to 5.25 psia, as shown by the lower broken line in Figure 2, before EVA may be safely attempted within the 1.5:1 ratio.

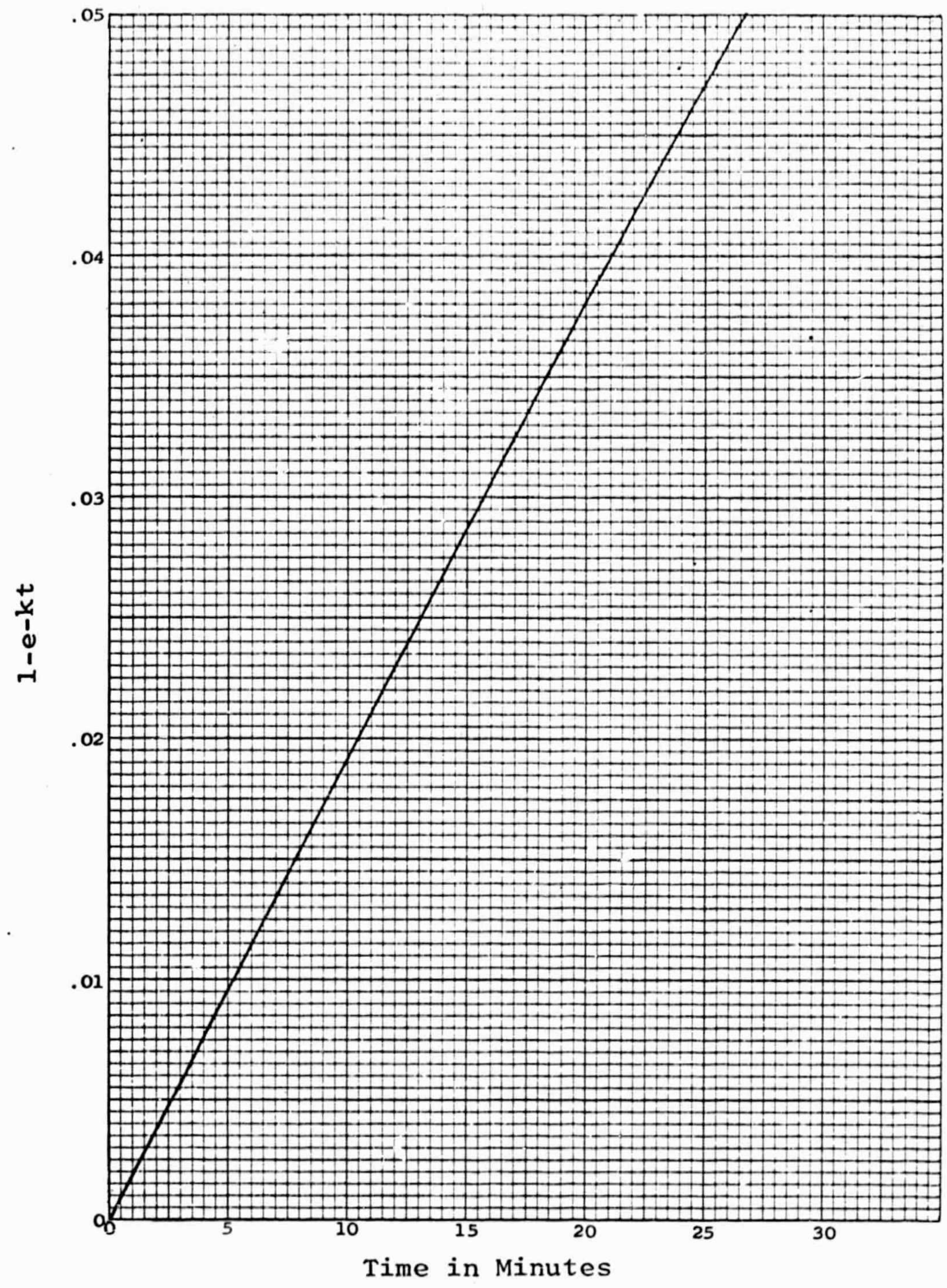

Figure 5. Nitrogen absorption rate in 360-minute half-time tissue.

When the astronaut is finally exposed to the cabin atmosphere at the predetermined cabin pressure of 5.6 psia, his nitrogen tissue tension, as obtained from Figure 2, is then plotted on the appropriate nitrogen-oxygen breathing-mixture curve of either Figure 3 or 4 (or on the next higher percentage, if the exact one does not appear on the graph).

From the time interval during which the indicated breathing mixture is used, one can determine the nitrogen tissue tension that would exist at any given interval after beginning respiration of that mixture. If the nitrogen percentage in the cabin drops to a lower value than that which appears on the graph, the tissue tension taken from the previous mixture can then be applied to the appropriate curve corresponding to this new nitrogen percentage. The nitrogen partial pressure can be plotted against the time duration along this curve. In all cases, the exact percentage shown on the curves, or the NEXT HIGHER ONE, should be used. This process can be repeated as often as the flight situation requires.

Using these curves (with preoxygenation time of 3¼ hours prior to decompression to 5.6 psia), EVA may be effected without danger of decompression sickness after an additional period of 5 hours breathing oxygen, 6¼ hours breathing 40%N_2-60%O_2, 5½ hours breathing 30%N_2-70%O_2, or 5.1 hours breathing 20%N_2-80%O_2. An alternate solution would be to extend the period of denitrogenation by housing the astronauts prior to the flight in enclosed quarters in which an atmosphere of oxygen-enriched air is supplied.

An atmosphere of 20%N_2-80%O_2 at sea level will reduce the tissue tension in the 360-minute half-time tissue to 6.38 psia after 8 hours. This will permit a safe reduction to the stipulated cabin pressure, and EVA can be safely commenced within the desired supersaturation ratio after an additional period of 2 hours on oxygen or 2½ hours on a 40%N_2-60%O_2 mixture at cabin pressure.

If a 40%N_2-60%O_2 rather than a 80%N_2-20%O_2 mixture is used at sea level, 16 hours of prebreathing will produce a tissue tension of 6.78 psia. This procedure permits a direct reduction to cabin pressure, and after a period of 2½ hours on oxygen--or 3 hours further breathing a 40%N_2-60%O_2 mixture at a cabin pressure--would permit a scheduled EVA within the stipulated supersaturation ratio.

Optimum reduction of time would result from an oxygen-enriched breathing mixture combined with reduced pressures prior to flight. If the astronauts were enclosed in a hypobaric chamber at a pressure of 9 psia (13,000 feet altitude), a tissue tension of 5.25 will result from 8¼ hours of oxygen-breathing, permitting a direct decompression to an EVA pressure of 3.5 psia any time thereafter. Once they have left the hypobaric chamber, the astronauts' nitrogen tissue tension can be maintained indefinitely at that level by their breathing a nitrogen-oxygen mixture containing 35% nitrogen, or less, at sea level.

If it is desired, other atmospheres can be used at the above-mentioned altitude in place of oxygen. If an atmosphere of 30% nitrogen-70% oxygen were used at the 13,000-foot altitude, a direct decompression to 3.5 psia could be safely achieved after 9 hours spent breathing that mixture. The same mixture (or 35% nitrogen-65% oxygen) can then be used to maintain the desired tissue tension until liftoff.

The astronauts' period of sleep prior to flight could be effectively used to lower tissue tension to the desired value. It could then be maintained at this value until liftoff, thus eliminating the problems involved in achieving the proper tissue tension just prior to and during the mission.

THE USE OF INERT GASES OTHER THAN NITROGEN IN CABIN BREATHING ATMOSPHERES

Other inert gases, such as helium and argon, have been used to advantage in diving procedures to reduce decompression time from exposure to elevated pressures. For maximum effectiveness, inert gases are used singly, in sequence, or in combination with one another, according to the depth and duration of the dive and the particular operating conditions imposed. In all cases, however, the maximum rate of elimination of inert gas from the body is obtained by breathing oxygen.

Inert gas-oxygen mixtures are used in diving procedures during decompression only when it is inadvisable, for one reason or another, to use oxygen. It must be borne in mind that, in any event, from the outset of breathing inert-oxygen mixtures, the tissues already contain a quantity of nitrogen that must be combined with whatever inert gas is chosen to replace it in the breathing medium at cabin pressure.

To determine the effectiveness of substituting another inert gas for nitrogen in the breathing mixture, one must calculate the degree of saturation in the bodily tissues of the inert gas (which we will call B) and the amount of nitrogen (which we call A) eliminated from the body at the end of a specified time period. The supersaturation ratio is applied to the total sum of the partial pressures of the gases considered.

If it is desired to eliminate nitrogen from the tissues at a more rapid rate by switching to inert gas B, the latter inert will go into solution while the former is being eliminated. The net advantage of this method is indicated by application of the appropriate supersaturation ratio to the value A+B, as opposed to the ratio applied to the value A (which would have resulted if one had elected to remain on nitrogen alone) after a given period of time.

Although the permissible safe supersaturation ratio will vary according to the individual gases used, regardless of the specific time interval involved, there nevertheless will be a considerable quantity of residual nitrogen in the body in comparison with the quantity of inert gas in solution in the slowest tissues. Nitrogen is, therefore, of great importance in determining the supersaturation ratio. Hence the nitrogen supersaturation ratio may be used in the preliminary assessment of the relative merits of various inert-gas substitutions for nitrogen in specific circumstances.

After nitrogen, helium is the inert gas most widely used with oxygen to form the breathing mixtures of divers. Many authorities agree that helium[3,4], and probably hydrogen[5], will saturate and desaturate the tissues more rapidly than nitrogen will. Therefore, if an inert gas such as hydrogen or helium is used to replace nitrogen in the breathing mixture at altitude, and the percentage of oxygen is the same, the nitrogen will be eliminated at approximately the rate shown on Figure 2, while the hydrogen or helium will be absorbed by the tissues at a more rapid rate. The effect after several hours is a higher total inert partial pressure in the tissues than if nitrogen had been used. The use of these inert gases should, therefore, significantly lengthen the time interval before EVA can be safely undertaken.

As an example: after 4 hours of preoxygenation, followed by an additional 4 hours at 5.6 psia in which a 50%N_2-50%O_2 mixture has been breathed, the partial pressure of nitrogen in the 360-minute half-time tissue will be reduced to 6 psia. If an inert gas having an uptake and elimination rate twice that of nitrogen were substituted during the latter 4 hours, the sum of the partial pressures would be slightly in excess of 7 psia, with a nitrogen to inert-gas ratio of approximately 2:1. Use of such an inert gas, therefore, would retard the reduction of tissue tension beyond that which could be compensated for by a slight increase in the supersaturation ratio, and would be a disadvantage because the time required in breathing a cabin mixture before undertaking EVA is thereby lengthened.

However, if an inert gas were used--*e.g.*, krypton, xenon, or argon--which shows evidence of having much slower uptake and elimination times than nitrogen, some advantage would be gained toward the reduction of tissue tensions. Part of the advantage would be offset, however, by a slight reduction in the permissible supersaturation ratio. Although the outward partial pressure gradient for nitrogen would be maximal P_a-P_o=0 (as would be the case if pure oxygen were used), there would be, at the same time, an inward gradient for the inert gas having a slower uptake and elimination time. Hence the resulting total partial pressure of nitrogen plus another inert gas would be greater than if oxygen alone were used.

Maximum advantage is always obtained, within the specific pressure-time limits considered here, through the use of pure oxygen as a breathing medium. If oxygen alone is breathed in the entire period prior to EVA, rather than a preoxygenation period of 3¼ hours followed by a 40%N_2-60%O_2 cabin mixture breathed at 5.6 psia, only 2¼ hours overall time is saved to the point in time where EVA could safely be commenced (Figure 6).

From a technical standpoint, the possible net gain to be realized by using an inert gas having a greater uptake and elimination time than nitrogen is very small compared with the complexity of substituting other inert gases.

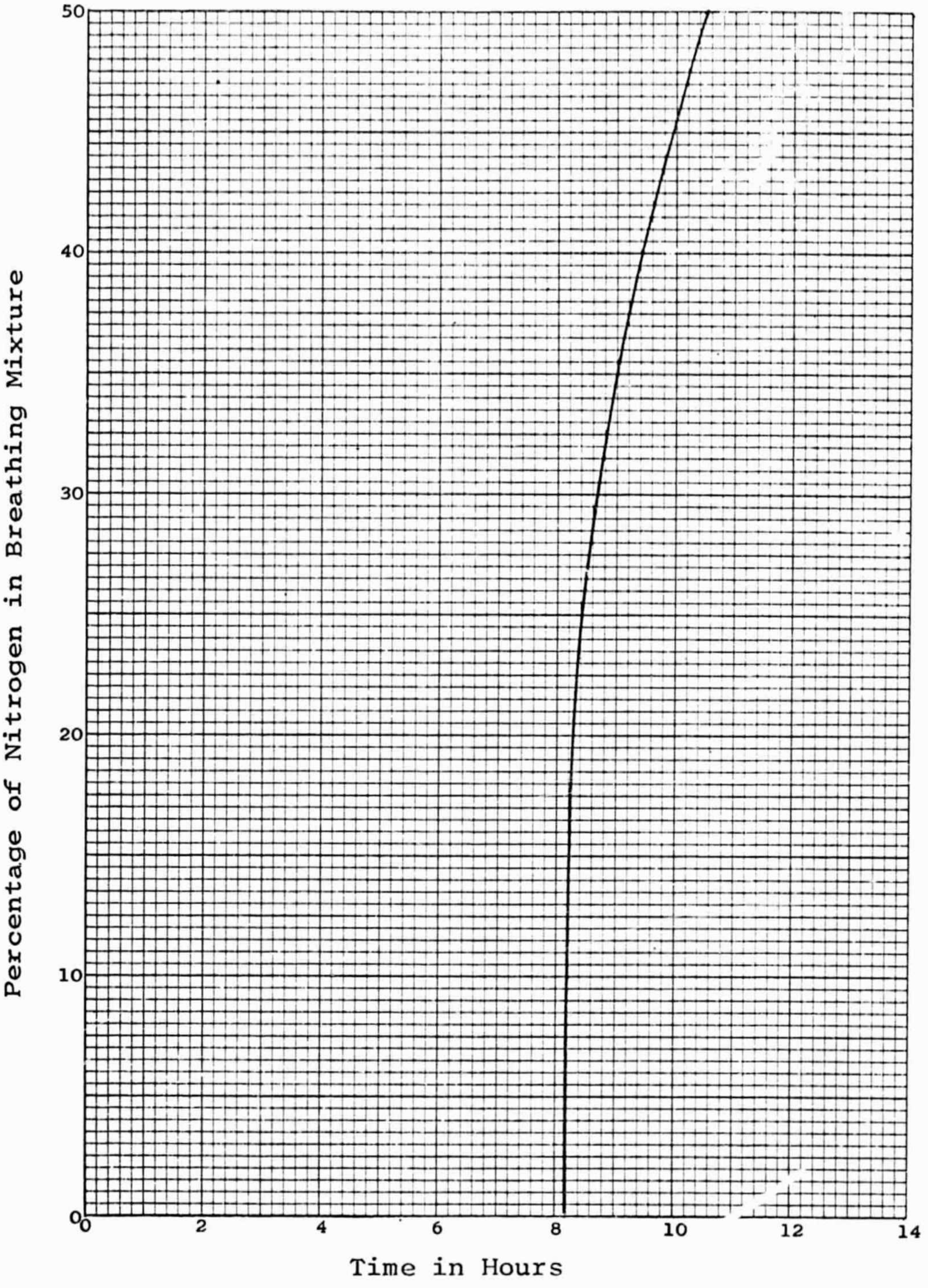

Figure 6. Denitrogenation time considered safe before decompressing from 5.6 psia to 3.5 psia (including 3¼ hours of denitrogenation by breathing oxygen).

EFFECTS OF VARIATIONS IN CABIN PRESSURE

Any significant deviation from a cabin pressure of 5.6 psia renders calculations based upon that specified pressure invalid, and makes decompression sickness a probability. If crew members are exposed after liftoff to a pressure greater than the one programmed, the percentage of inert gas specified for use at 5.6 psia in the cabin atmosphere will exert a higher partial pressure than the one calculated for, decreasing the gradient for elimination. This decrease will, in turn, reduce the rate at which nitrogen is removed from the controlling, or slowest, tissue. The reduced rate of nitrogen elimination will cause a higher supersaturation ratio on EVA if the schedule calculated for a cabin pressure of 5.6 psia were used to determine the EVA time.

Unless there is a corresponding increase in preoxygenation time, a cabin pressure lower than the anticipated one will cause a greater supersaturation ratio, predisposing the astronaut to the formation of bubbles in his bodily tissues. For example: almost 4 hours of preoxygenation is required to effect a 1.5:1 ratio upon arrival if the capsule pressure is 5.4 psia, as opposed to 3¼ hours of preoxygenation prior to arrival if the capsule pressure is 5.6 psia.

ASSUMED CONDITIONS PRIOR TO OXYGEN BREATHING

To predict the probability of decompression sickness in astronauts during EVA, or as a result of an unscheduled reduction in cabin pressure, it must be assumed that certain conditions existed prior to these pressure changes.

First of all, it is assumed that during the 48 hours prior to liftoff, the subjects have not had any sort of exposure to pressure--such as in SCUBA diving--appreciably greater than that at sea level; and that they have not breathed any gas mixture--or at least have done so only briefly--other than air or oxygen. It is further assumed that during this period the subjects have not been exposed to any form of pressure reduction--*e.g.*, aircraft flights or decompression in altitude chambers exceeding the equivalent of 15,000 feet altitude. This is to ensure against any prior formation of bubbles in the tissues which would adversely affect the body's tolerance, temporarily, to further pressure changes.

The further assumption is made that the crew members have been free from any symptoms of decompression sickness for a minimum period of two weeks prior to the day of launch. The sites of tissue damage caused by a recent attack of bends might become the focal points for bubble formation when the pressure is further reduced to that of capsule pressure or EVA.

VARIATIONS IN SUSCEPTIBILITY TO DECOMPRESSION SICKNESS OWING TO CONSTITUTIONAL FACTORS

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 occur in a particular subject. 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.

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[6], and (2) require less preoxygenation time for protection against bends than older crew members do[7].

However, there are significant variations in resistance to bends among members of same age groups, which may possibly be attributed to difference 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[6]. The constitutional factors that appear to render an individual susceptible may, in fact, be simply a relationship between the rate of uptake and elimination of nitrogen in the tissue, which in turn may alter the individual's tolerance to supersaturation. It has been observed on testing decompression profiles[3] that "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.

EFFECT OF EXERCISE ON OCCURRENCE OF DECOMPRESSION SICKNESS

The rate at which nitrogen is eliminated during 100% oxygen breathing may vary slightly during ordinary daily activities, but not to a significant degree. However, if the subjects engage in strenuous exercise following a pressure reduction, there is a marked increase in the probability of bends and the rapidity of their development[8,9]. A preoxygenation schedule that provides protection against bends for 80% of the subjects who are at rest while exposed to a given altitude, may be effective for only 60% of them if they perform strenuous exercise at the same altitude. The site of pain of decompression sickness is also influenced by the specific exercise engaged in[10]. If the subjects are at rest at altitude, almost half of them report symptoms in knees and shoulders, in equal proportion. If the subjects engage in knee exercise, 70% of them report bends symptoms in the knees.

RESULTS OF EXPERIMENTATION TESTING THE THEORIES HEREIN PRESENTED

Three experiments, each involving two subjects, were conducted to verify the hypothesis that an inert-gas supersaturation ratio of 1.5:1 for a 360-minute one-half saturation time tissue can be used to calculate safe decompression profiles for space flight programs. The subjects had all previously participated in decompression experimentation in hyperbaric pressures, and were therefore familiar with the symptoms of decompression sickness.

The initial cabin pressure was maintained at 5.4 psia, and the cabin atmosphere contained a maximum of 45% nitrogen and 55% oxygen. Within these conditions, calculations indicate that 4 hours' preoxygenation time followed by 5 hours' breathing the specified mixture should result in maximum protection against bends in an EVA exposure. As this procedure is extremely conservative with respect to usual diving standards of safety, the cabin pressure used in Test #1, Figure 7, was 9.3 psia. The increased nitrogen partial pressure retarded the elimination of nitrogen prior to EVA by decreasing the outward pressure gradient of nitrogen in the tissues, thus biasing Test #1 toward increasing the probability of bends.

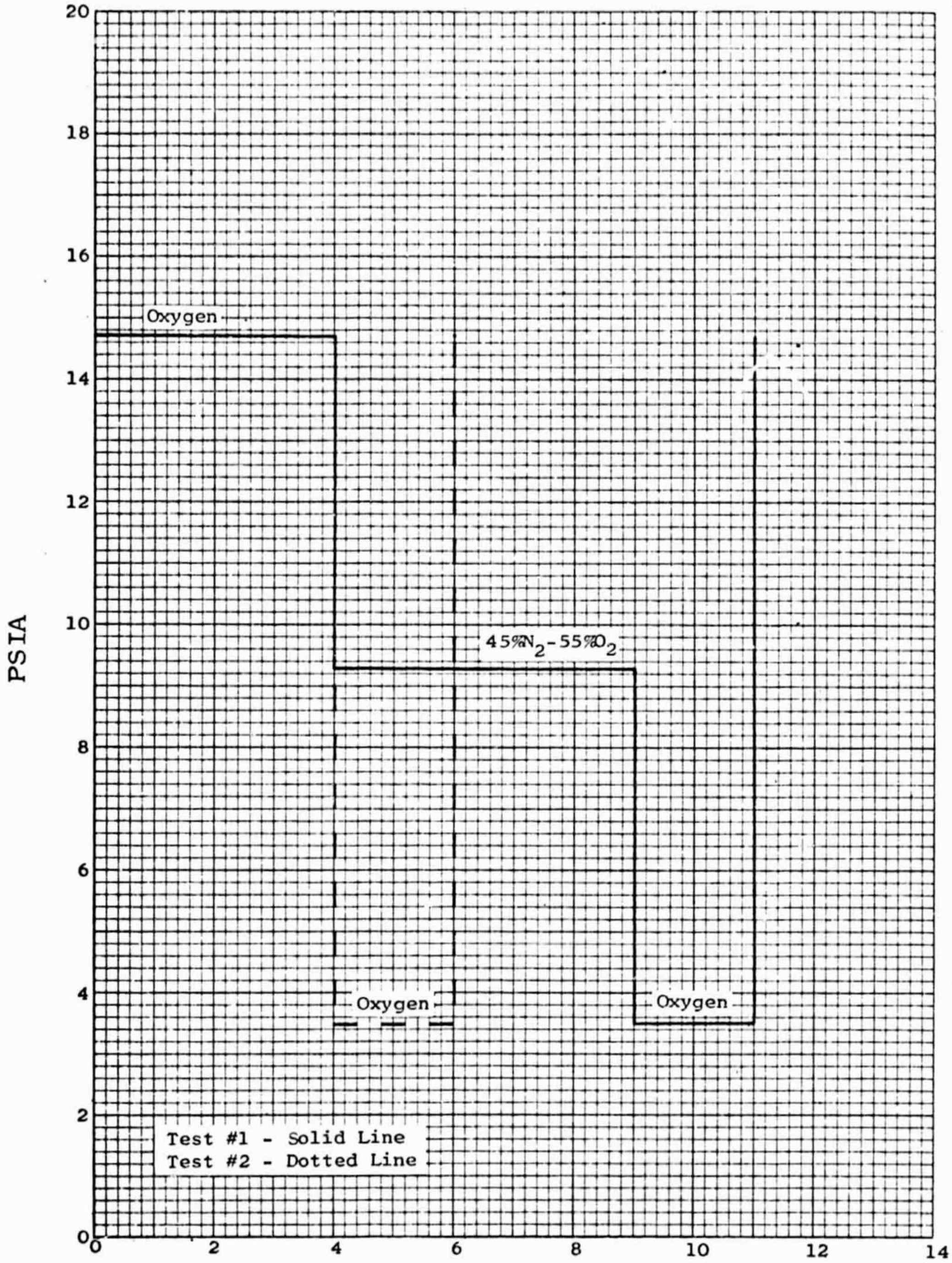

Figure 7. A profile of two pressure exposures which includes a 4-hour preoxygenation period at surface pressure.

In Test #1, accordingly, the two subjects were preoxygenated at sea level for 4 hours, were brought to 9.3 psia, and were held at that pressure for 5 hours while they breathed the $45\%N_2$-$55\%O_2$ mixture. The subjects then breathed oxygen, and the pressure was decreased to 3.5 psia. The subjects were held at the latter pressure for 2 hours, during which time they did not experience any symptoms of decompression sickness.

The two subjects in Test #2, Figure 7, were also preoxygenated for 4 hours at sea level, and were then directly exposed to 3.5 psia for 2 hours. These two subjects likewise experienced no symptoms of decompression sickness.

In Test #3, Figure 8, two subjects were preoxygenated at sea level for 3¼ hours, and were then brought to 5.6 psia and held at that pressure for 2½ hours, during which time they breathed a $40\%N_2$-$60\%O_2$ mixture. The subjects then breathed oxygen, and the pressure was decreased to 3.5 psia and held there for 2 hours. No symptoms of decompression sickness were experienced by either of these subjects.

Despite the consistency of the results in these three tests, it must be borne in mind that the use of two subjects only in each of the experiments does not constitute a statistically significant sample.

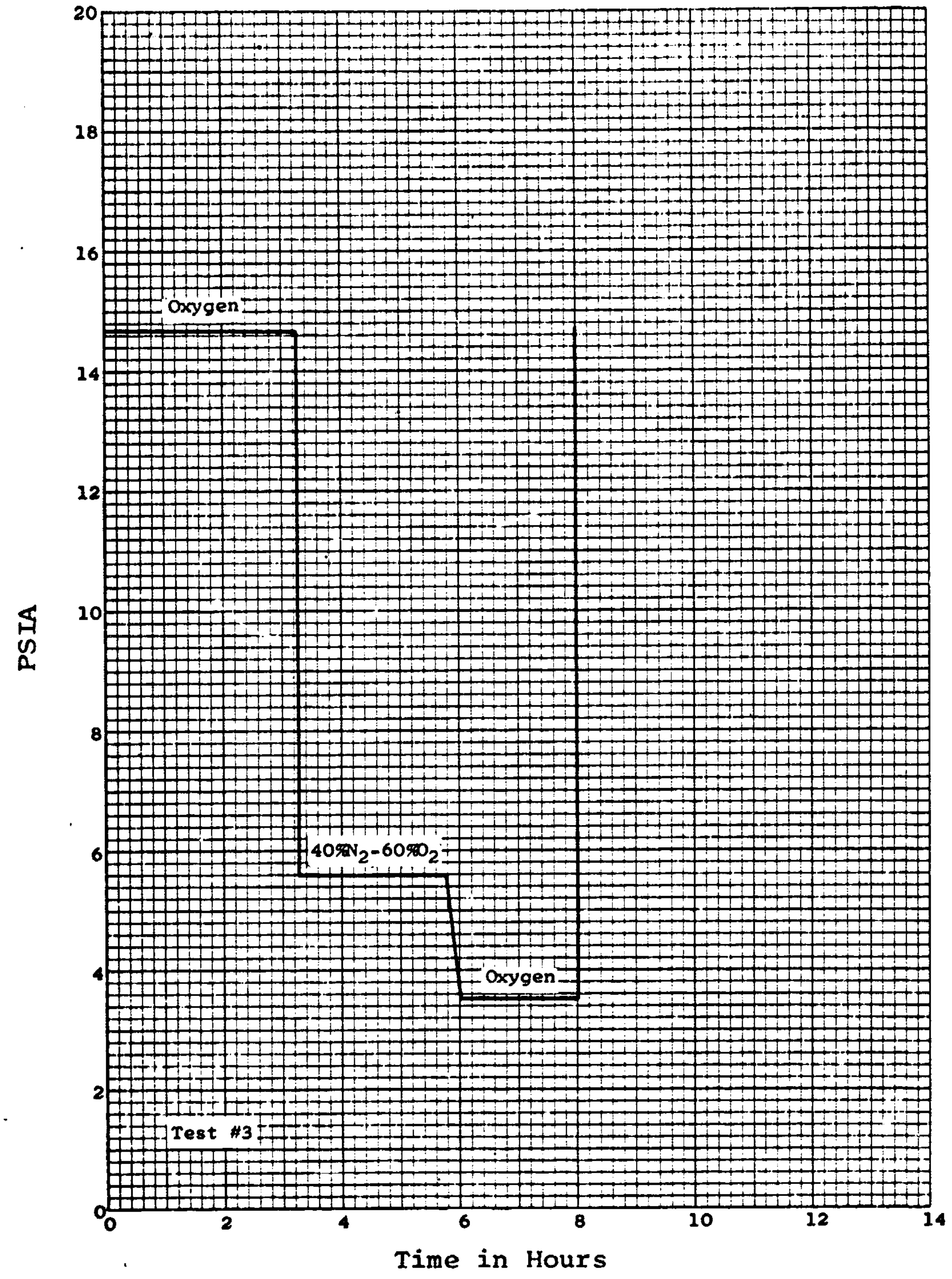

Figure 8. A profile of a pressure exposure which includes a 3¼ hour preoxygenation period at surface pressure.

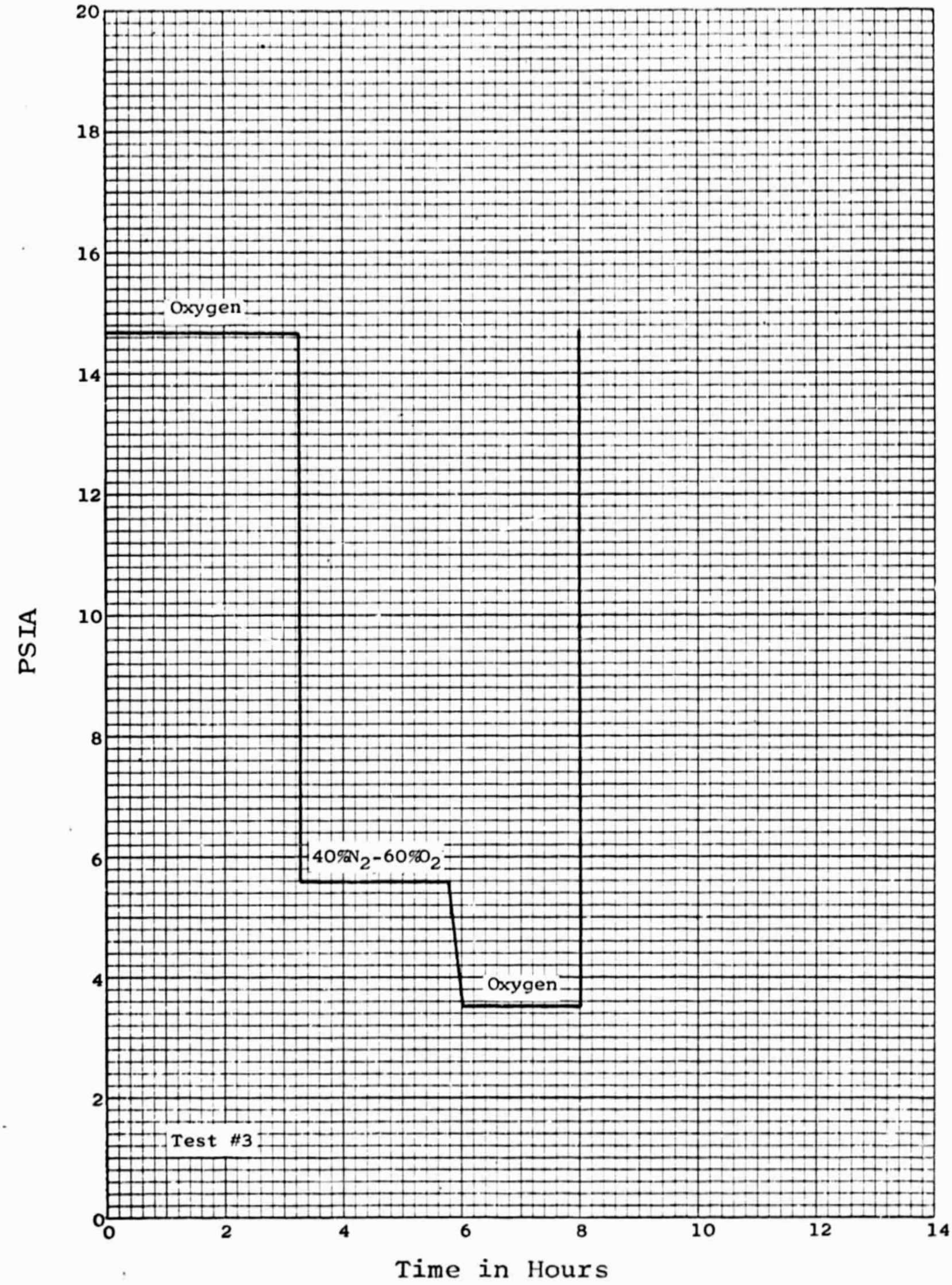

Figure 8. A profile of a pressure exposure which includes a 3¼ hour preoxygenation period at surface pressure.

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