The following item is excerpted from Apollo Accident, Hearing before the Committee on Aeronautical and Space Sciences, United States Senate, Ninetieth Congress, First Session, Part 1, Washington, D. C., February 7, 1967, pp. 16 and 17.

"Mercury Environmental Control System

"Early in the design phase, the Mercury spacecraft environmental control system had a launch oxygen purge system. This system was so designed that when the spacecraft was launched, cabin gas would be exhausted until an altitude of 27,000 feet (5 psia) was reached. At this altitude, the cabin relief valve would seal the cabin at this pressure. The launch purge supply worked as follows. On the pad, air was to be present in the cabin. After launch when the spacecraft passed 10,000 foot altitude, a flow of oxygen from a 1-pound supply was to be activated. This flow of oxygen enriched the cabin so that at 27,000 feet, the cabin composition was approximately 66 percent oxygen and 33 percent nitrogen.

"Manned tests on the life support system were started in April 1960. During the first test, the subject, Mr. North of McDonnell, became unconscious due to hypoxia. This incident occurred approximately 1 hour after the test. The cause of this failure was due to a nitrogen leak into the life support system suit loop. The nitrogen built up to a concentration where sufficient oxygen partial pressure was not available to maintain consciousness. This initial failure was due to leaks in the instrumentation lines exterior to the space chamber and the suit loop system. Nine additional manned tests were conducted and subsequent problems were encountered in the maintenance of space suit oxygen partial pressure. This decrease in suit $_pO_2$ was caused by negative ΔP between the suit and cabin systems. In all of these and subsequent tests, oxygen partial pressure dropped in the space suit loop.

"Based on these failures to maintain oxygen partial pressure levels at nearly 100 percent in the space suit loop, action was initiated to correct this situation. It was decided to

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remove the launch oxygen purge supply and provide a 100 percent cabin purge on the pad prior to launch. McDonnell Aircraft Corporation Change Nos. 280 (A) and 285 were issued.

. . . .

"The requirement for purging the cabin with pure oxygen at approximately 15 pounds per square inch during the prelaunch period of several hours has been continued for all manned spacecraft launched in this country. This same procedure has been used also on all manned spacecraft vacuum chamber tests in the Mercury, Gemini and Apollo Programs."

(1)

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EARLY MERCURY
ENVIRONMENTAL CONTROL SYSTEM

- AIR IN CABIN ON PAD.
- 1 LB. O_2 ENRICHMENT.
- 10 CHAMBER TESTS HAD IN SUIT N_2 LEAKS.
- 100 PER CENT O_2 ON-PAD SOLUTION.

MSC-DA/4-3-68

POSITION AFTER 204 ACCIDENT

- CHANGE SPACECRAFT MATERIALS TO NONFLAMMABLES.
- REDUCE IGNITION SOURCES.
- IMPROVE CREW EGRESS.
- SPACECRAFT FLAMMABILITY TEST.

MSC-DA/4-3-68

TOXICOLOGY PROBLEM

- DIFFICULT TO DETERMINE <u>ALL</u> MATERIALS AND AMOUNTS IN SPACECRAFT.
- FORCED TO END ITEM TEST.
- NEED 12-HOUR UNMANNED RUN - PROGRAM IMPACT.
- TOXIC PYROLYSIS PRODUCTS FROM NEW MATERIALS.

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ATMOSPHERE FACTORS

- PHYSIOLOGICAL REQUIREMENTS.
- ENGINEERING CONSIDERATIONS.
- OPERATIONAL CONSIDERATIONS.

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ATMOSPHERE OXYGEN GOALS

- POOR PERFORMANCE OF CREW.
- NO ADAPTIVE MECHANISMS TRIGGERED.

(6)

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PHYSIOLOGICAL GROUND RULES

1. ATMOSPHERE MUST PROVIDE SEA LEVEL PAO_2 OR HIGHER.

2. IF ATMOSPHERE VIOLATES ABOVE AT ORBITAL INSERTION, IT MUST BE ENRICHED.

3. SUIT LOOP 0_2 MUST BE 95 PER CENT FOR EVA.

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MEDICAL REQUIREMENTS
FOR USE OF 60/40 ATMOSPHERE

- TEST OF 60/40 WITH SPACECRAFT SYSTEM.
- POSITIVE PRESSURE IN SUIT.
- ACCURATE ΔP BY T/M.
- ACCURATE $_{P}O_2$ SENSOR - CABIN AND SUIT.

EVALUATION OF NITROGEN/OXYGEN MIXTURES ON THE PAD

Physiological Capability

Any proposed breathing mixture must be evaluated in terms of its inherent risk for the development of hypoxia and/or dysbarism.

Hypoxia. Figure 1 is a graphic presentation of the relationship of oxygen partial pressure to percentage saturation of human blood with oxygen. It is to be noted that the sigmoid shape of the curve results in a condition such that at oxygen pressures in excess of 60 mmHg there is very little change in percent saturation of arterial blood. Below about 50 mmHg oxygen tension a relatively small decrease serves to unsaturate the hemoglobin molecule rather precipitously. The center curve, Ph = 7.4, represents the normal condition for human blood.

Atmospheric air at sea level pressure contains approximately 21% oxygen by volume. When air is inspired into the trachea it is immediately saturated with water vapor by contact with the respiratory mucosa. Assuming that dry air had been inspired at pressure of 760 mmHg, the addition of moisture to the tracheal air serves to lower the total pressure of the other gases, namely nitrogen and oxygen. So that their combined pressures now total 713 mmHg (the vapor pressure of water at body temperature is 47 mmHg, thus 760-47 = 713). Tracheal air contains a partial pressure of oxygen of 149 mmHg (21% of 713). When this gas reaches the alveolar spaces and gas exchange takes place across the pulmonary membranes, oxygen is absorbed by the hemoglobin within the red blood cells according to the middle curve in Figure 1. As oxygen is absorbed, carbon dioxide is released from the blood and diffuses into the alveolar spaces of the lungs. If the volume of carbon dioxide released into the alveolar spaces per unit of time is equal to the volume of oxygen leaving the alveolar spaces in that time, the exchange ratio is said to be one. Thus, respiratory exchange ratio

$$(R) = \frac{\text{volume } CO_2 \text{ produced}}{\text{volume } O_2 \text{ consumed}}$$

Because of factors relating to complex metabolic processes and the fact that when a diet of fats, proteins and carbohydrates is consumed, and metabolized by a variety

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of organs, each with its own pattern of metabolism, the net effect is that the gas exchange in the lungs does not produce a respiratory exchange ratio of one, but more nearly 0.84. When air or a similar gas mixture is breathed, the effect of R being less than one has a minor but significant influence on the calculation of composition of alveolar gas. So taking this into consideration, we calculate the composition of alveolar gas with respect to oxygen as

$$P_{A_{O_2}} = F_{I_{O_2}} \left(P_B - P_{A_{H_2O}} \right) - P_{A_{CO_2}} \left[F_{I_{O_2}} + \frac{1 - F_{IO_2}}{R} \right]$$

Where: $P_{A_{O_2}}$ = Partial pressure, alveolar oxygen

$F_{I_{O_2}}$ = Mole fraction, inspired oxygen

P_B = Barometric pressure mmHg

$P_{A_{H_2O}}$ = Partial pressure water at 37° C

$P_{A_{CO_2}}$ = Partial pressure alveolar carbon dioxide (this is normally about 40 mmHg, held relatively constant by the action of the nervous system in regulating the rate and depth of breathing).

R = Respiratory Exchange Ratio

It can be shown by the above formula that when air is breathed at sea level the oxygen partial pressure in the alveolar gas is about 102 to 104 mmHg. (see Figure 6.)

Because some blood traverses the lung without coming into contact with alveolar gas for exchange, the arterial blood reaching the left ventricle for ejection into the body systems, never quite reaches 100 percent saturation but rather may be saturated to the extent of about 97.5 percent. When the oxygen tension of the alveolar gas is caused to decrease for any of several reasons (reduction of the total atmospheric pressure, intentional or accidental alteration of the composition of the inspired gas, tracheal-bronchial obstruction, disease, higher than normal body temperature, etc.) the oxygen carrying capacity of the blood is impaired and the saturation falls accordingly. Figure 2 portrays graphically the range of arterial oxygen tension (arterial oxygen tension essentially equals alveolar oxygen tension) at which various undesirable physiologic effects have their onset in a normal resting man.

It should be noted that below 60 mmHg arterial oxygen tension relatively small changes in arterial oxygen tension quickly lead from acceptable to unacceptable levels of performance. Figure 5 illustrates why this is so. The transfer of oxygen from the blood stream to the utilizing tissues is in large measure dependent upon diffusion. Points A and A' represent arterial oxygen partial pressure at sea level and at 22,000 feet respectively. Points V and V' represent venous oxygen partial pressure at the same altitude. The A - V difference represents the working pressure of oxygen available in the capillary bed to effect the diffusion of oxygen from the blood into the surrounding tissues. Assuming the same oxygen utilization for both conditions the arterial venous pressure difference is much less at altitude than at sea level. The contrast is even greater when the oxygen utilization is reduced by increased cardiac output (A' - V").

It is evident from Figure 3 that a satisfactory and very normal alveolar oxygen tension may be obtained at any cabin altitude from sea level to about 35,000 feet equivalent altitude or 3.5 psi (note that the total pressure psi plot begins at 2 psi and not zero), by mixing oxygen with an inert diluent gas in proportions that satisfy the alveolar gas equation for 104 mmHg.

Figure 6 graphically compares the alveolar gas composition under sea level conditions in air with two conditions in 60% oxygen, 40% nitrogen, and the worst case situation in which a cabin atmosphere which was 60% oxygen, 40% nitrogen at launch could result in a 48% oxygen, 52% nitrogen atmosphere at 4.8 psi before enrichment by the cabin pressure regulator begins.

It will be noted in Figure 3 that a sea level equivalent alveolar oxygen tension of 104 mmHg provides a considerable safety factor in terms of percent arterial saturation and consequently in protection against symptomatology and performance decrements. A physiological ground rule stating a requirement for a cabin atmosphere physiologically equivalent to sea level conditions was chosen after careful consideration and a review of several reports by recognized physiological authorities who have addressed themselves to the problem of spacecraft cabin atmosphere selection.

The altitude equivalent points of onset of physiological decrement shown in Figure 2 were predicated upon conditions existing in a healthy individual having 15 grams or more of circulating hemoglobin. Any situation resulting in decrease in the effective circulating hemoglobin mass will result in less oxygen carrying capacity in the blood. Examples of situations which could lead to a decrease in effective circulating hemoglobin are: poisoning of the hemoglobin molecule by inhalation of toxic substances such as carbon monoxide, loss of blood due to illness or injury, or the destruction of red cells by sequestration (The red cell mass loss noted on the longer Gemini flights is thought by most of our consulting hematologists to have been due to the effects of hyperoxia on the red cell membrane. However, some of these consultants do feel that sequestration of red cells as a result of blood volume redistribution in response to weightlessness may have played a significant role in the destruction of red cells. It has been impossible to investigate the hyperoxia hypothesis during the past year due to the nonavailability of oxygen rated altitude chambers. Testing of the sequestration theory must necessarily await flight programs in which it is possible to closely control the oxygen content of the atmosphere at or near sea level equivalent partial pressures.)

Emergency situations calling for increased work output or resulting in emotional or environmental stress upon the crewmen will result in an immediate increase in oxygen demand. When the oxygen concentration per unit volume of inspired gas remains constant, the increased amount of oxygen required by the tissues can be delivered only by an increased ventilatory rate and increased cardiac output (achieved in some measure by increased stroke volume but largely by increased stroke rate). A lower oxygen concentration in the inspired air in a subject at rest will also bring these compensatory mechanisms and others into play. As ventilatory depth and rate increase, the CO_2 content of the blood diminishes. This results in a shift in the acid base buffer system of the blood toward the alkylotic side which in turn triggers renal mechanisms which operate to adjust the electrolyte composition of the blood back to a homeostatic condition.

All the physiological data collected in Mercury and Gemini came from crewmen in an hyperoxic cabin atmosphere. Several physiologic changes (such as cardiovascular deconditioning, fluid recompartmentalization, red cell mass deficit, and bone demineralization) were identified. Although we feel confident that none of these departures from ground level homeostatic conditions will be detrimental to crew health or safety during the 14 day mission in hyperoxic or sea level oxygen equivalent atmospheres, we have no data which would allow us to predict the results of the interaction of the compensatory mechanisms brought into play by mild hypoxia with the spaceflight induced adaptive and/or degradative processes listed above. The collection of such data should be a part of future medical goals, but the injection into the Apollo Program of an effort to obtain these data certainly does not seem feasible. Neither does it seem prudent to embark upon such a rigorous and nationally important program as Apollo with a cabin atmosphere which unnecessarily raises any element of doubt about crew safety or performance.

Dysbarism. In a ground level 80 percent nitrogen atmosphere man's tissues are saturated with nitrogen. The tissue nitrogen tension is in equilibrium with the air nitrogen tension. If man is subjected to a reduced pressure environment, nitrogen diffuses out of the various tissues into the blood stream and is eliminated through the pulmonary system. The rate of elimination is dependent upon both the pressure gradient (tissue N_2/atmospheric N_2) and the diffusion rate of the various tissues, which in turn are dependent upon the circulatory perfusion. If the pressure gradient becomes great enough, bubbles of nitrogen may form in the blood stream and in various tissues. As the bubbles reach critical size they may result in symptomatology at the site of formation or they may be carried by the blood stream to distant points such as the pulmonary system or central nervous system. The most common symptom of dysbarism is the occurrence of local pain, commonly referred to as bends. Less common but still of significant incidence are blindness, paralysis, circulatory collapse and shock, which can result from central nervous system dysbarism.

Dysbarism may be protected against by reducing the nitrogen content of the body tissues to a tissue nitrogen tension at or below the N_2 partial pressure to which one expects to be exposed. This can be accomplished by breathing 100 percent oxygen for an adequate period prior to exposure to decreased atmospheric pressures. The time required for denitrogenation varies greatly from individual to individual and has been related to percent body fat, physical conditioning, age, and exercise.

Figure 4 plots the curve of the partial pressure of remaining nitrogen as a function of pressure and time for a given case. The case chosen represents the slowest theoretical tissue with a desaturation ½ time of 360 min. Curve A represents continuation on 100 percent oxygen, Curve B represents a situation when after 4 hours of preoxygenation, the subject has been switched to a 55 percent oxygen atmosphere at 5.4 psi. It can be seen that there is some bends risk, even in 100 percent oxygen at Apollo cabin pressures, but this has been found to be an acceptable risk. Experimental evidence indicates that following 2 hours of prebreathing, exposure to a suit pressure of 3.5 psi within the first 9 hours after reaching orbit, carries an unacceptable bends risk. See Attachment 1. It would appear that 4 hours of prebreathing would bring the dysbarism risk for planned EVA's back to an acceptable level. There is insufficient experimental data however, to support this conclusion at this time. Indeed, whatever mixed cabin atmosphere is chosen, the predicted dysbarism risk must be verified by chamber tests using subjects similar to the astronaut population.

Physiology Ground Rules:

1. An acceptable mission cabin atmosphere must provide a sea level equivalent PAO_2 or higher. (Table A lists PAO_2 values and arterial oxygen saturations for a variety of cabin atmospheric conditions.)

2. If the spacecraft is launched with an oxygen/nitrogen mixture which results in a cabin atmosphere after orbital insertion that violates rule 1, the atmosphere must be enriched to provide a sea level equivalent PAO_2. The crew may remove helmets and gloves under the following conditions:

   a. The cabin atmosphere provides a PAO_2 of at least 82 mm Hg*, and

   b. Enrichment procedures are under way which will ensure a sea level equivalent atmosphere (73% O_2 at 4.8 psia) within 4 hours of first crew exposure to that atmosphere.

3. The suit loop oxygen concentration for planned or prolonged operations at 3.75 ± .25 psia (EVA or pressurized return) must be at least 95%. This will result in a PAO_2 of 82 mm Hg* at 3.5 psia.

* 4,000 ft. air altitude equivalent
62% O_2 at 4.8 psia, 52% at 5.6 psia

4. Oxygen prebreathing time prior to launch should be 4 hours. Time in the spacecraft may be counted if the loop O_2 percentage is kept above 95 percent and there is no significant break in the oxygen procedures.

Assumptions:

1. Measurement of partial pressure of oxygen in both the suit loop and the cabin is available and the accuracy of measurement has been considered in calculating the flight plan stop purge O_2 %.

2. Exposure of the crew to less than a sea level equivalent PAO_2 requires at least a single point failure, and exposure of the crew to a PAO_2 less than 60 mm Hg requires a multiple failure.

Table A

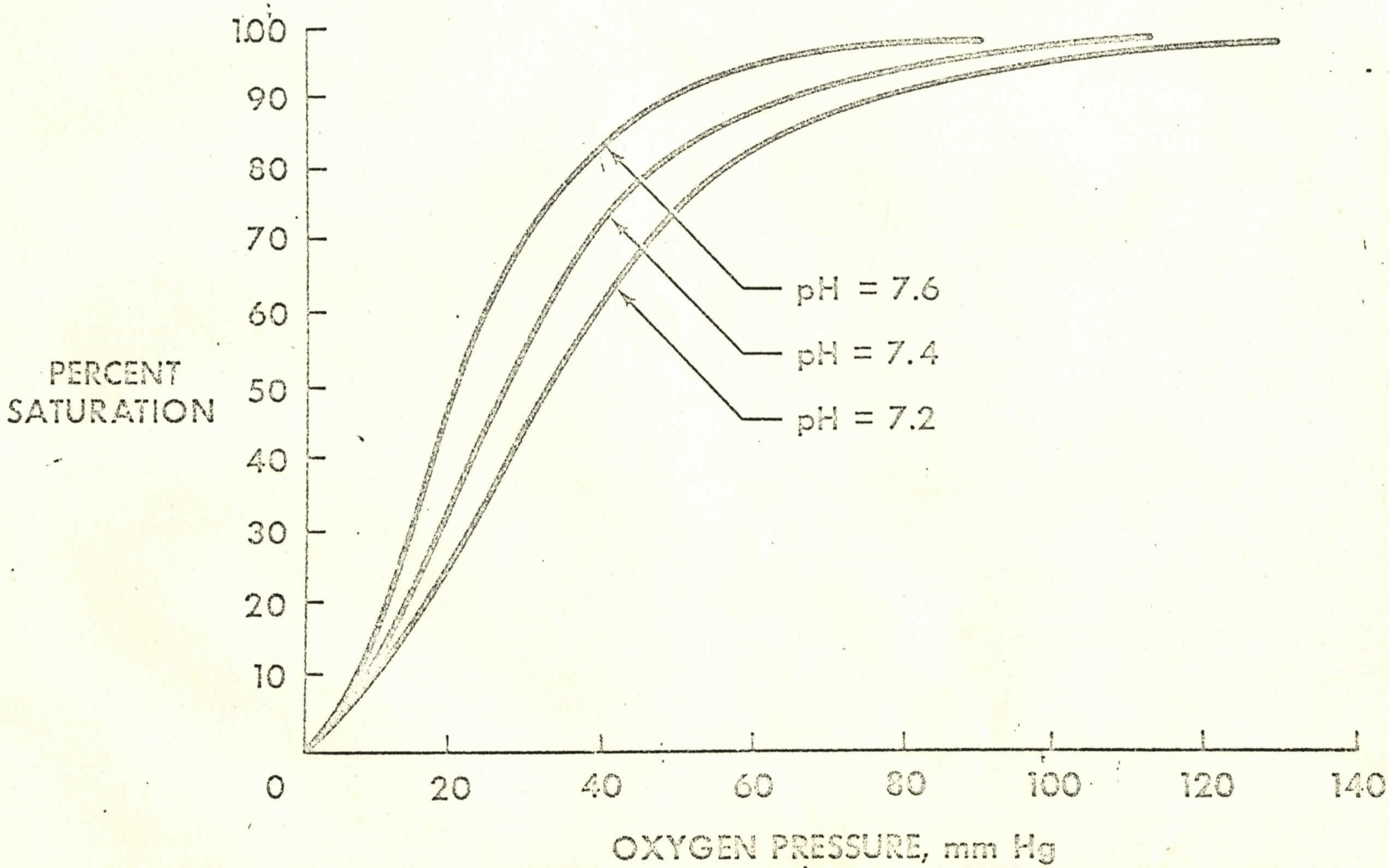
LUNG (ALVEOLAR) OXYGEN PARTIAL PRESSURES

AND OXY-HEMOGLOBIN SATURATIONS AT VARYING OXYGEN MIXTURES AND VARYING ATMOSPHERIC PRESSURES

OXYGEN MIXTURE	2.8 psi (145 mm Hg)		CONTINGENCY MODE MINIMUM PRESSURE 3.5 psi (181 mm Hg)		NOMINAL MINIMUM PRESSURE 4.8 psi (248 mm Hg)		PURGE MODE MINIMUM PRESSURE 5.6 psi (290 mm Hg)	
	PAO_2 mm Hg	OXY-HGB CONCEN %	PAO_2 mm Hg	OXY-HGB CONCEN %	PAO_2 mm Hg	OXY-HGB CONCEN %	PAO_2 mm Hg	OXY-HGB CONCEN %
AIR (20.93% O_2)/(79.07% N_2)			-18.0	0	-3.95	0	4.8	4
50% O_2/50% N_2			23.2	40	56.7	87	77.7	91
60% O_2/40% N_2			37.4	70	77.6	93	102.8	95
70% O_2/30% N_2			51.5	84	98.4	94	127.8	95
80% O_2/30% N_2			65.7	91	119.3	95	152.9	95
100% O_2/0% N_2	58	87						

NASA-S-68-113

OXYGEN DISSOCIATION CURVE OF THE BLOOD FOR DIFFERENT pH CONDITIONS



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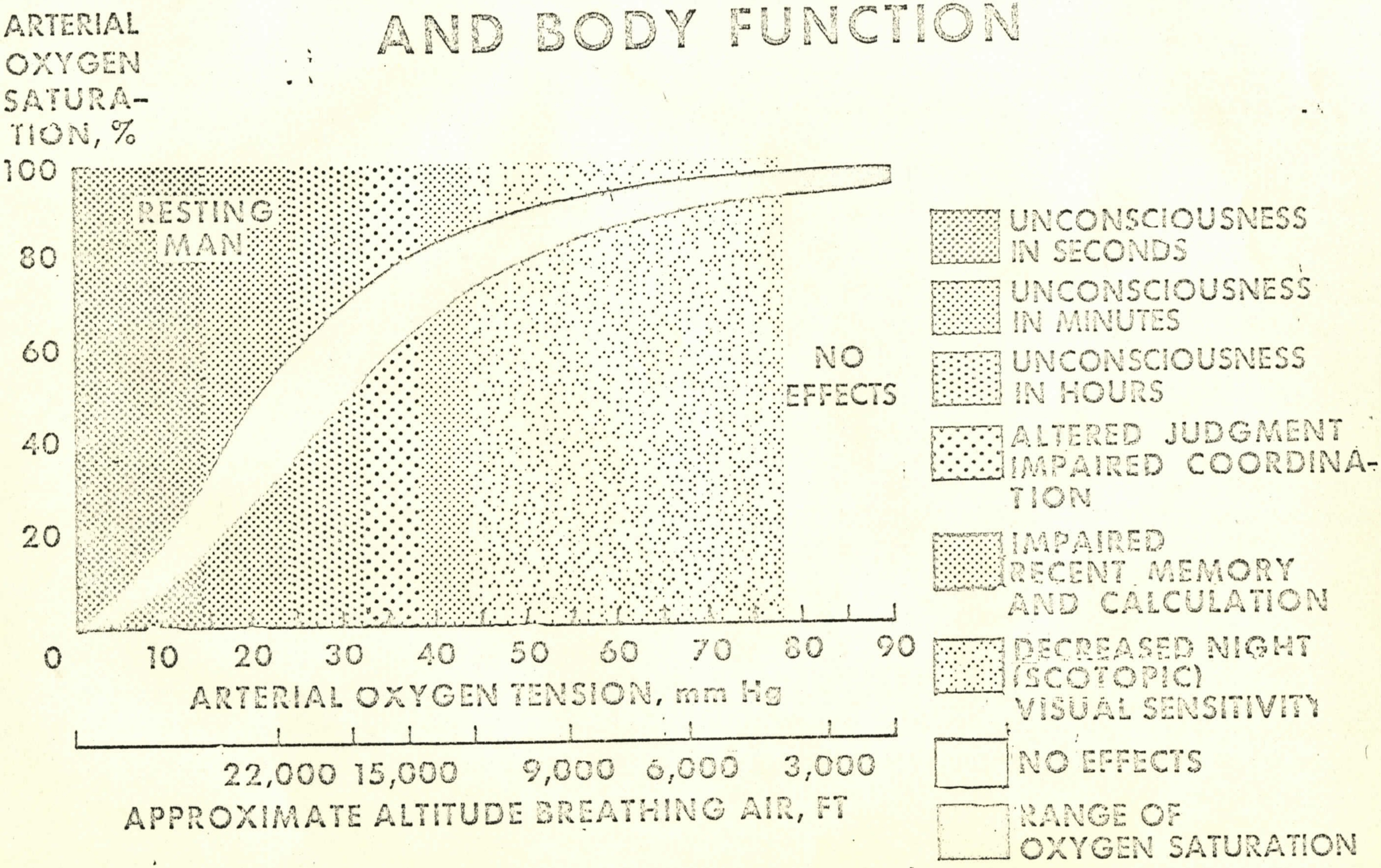
GENERAL EFFECTS OF HYPOXIA ON ARTERIAL SATURATION AND BODY FUNCTION



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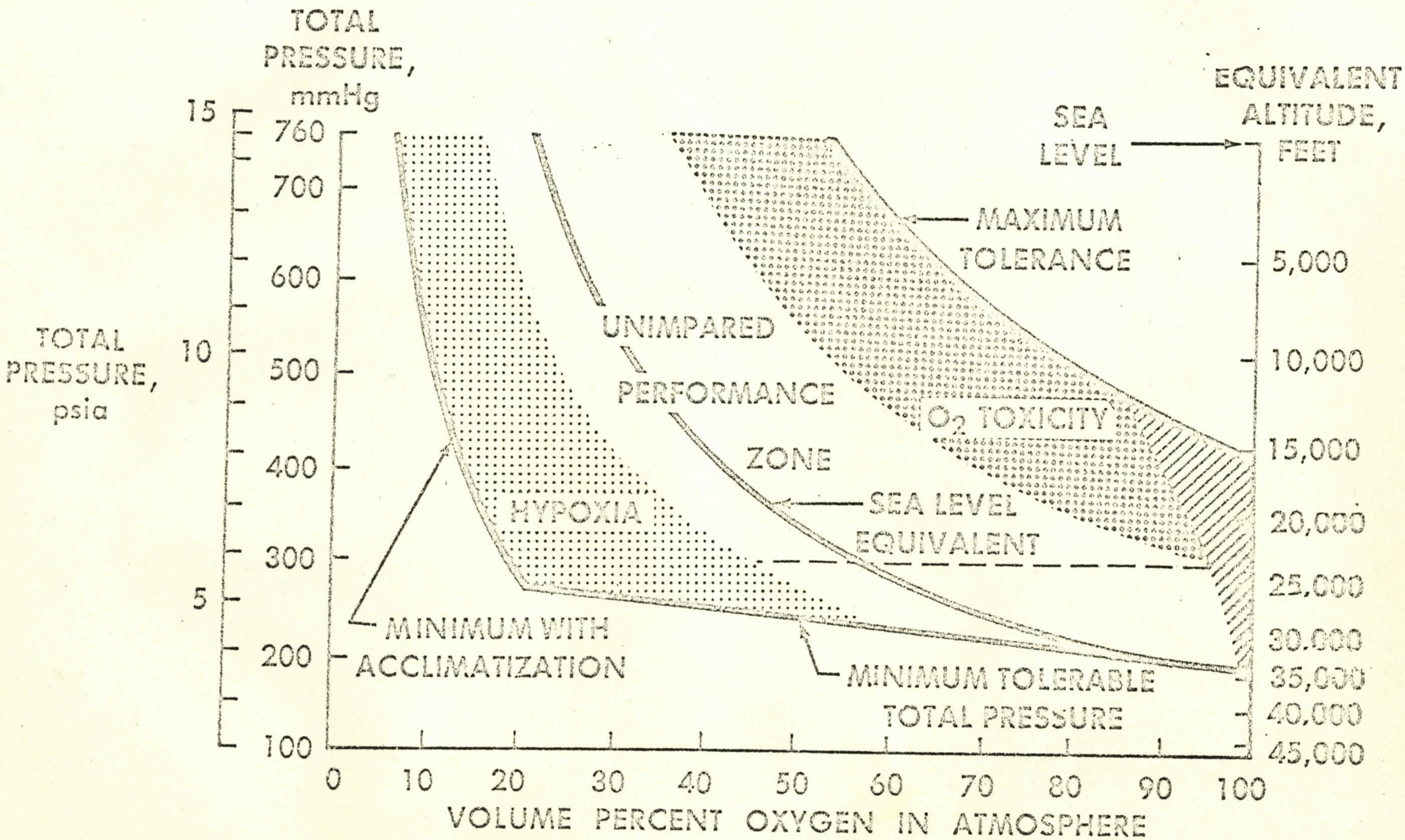
OXYGEN-PRESSURE EFFECTS



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CRITICAL TISSUE NITROGEN ELIMINATION CURVE

TISSUE 1/2 TIME 360 MINUTES

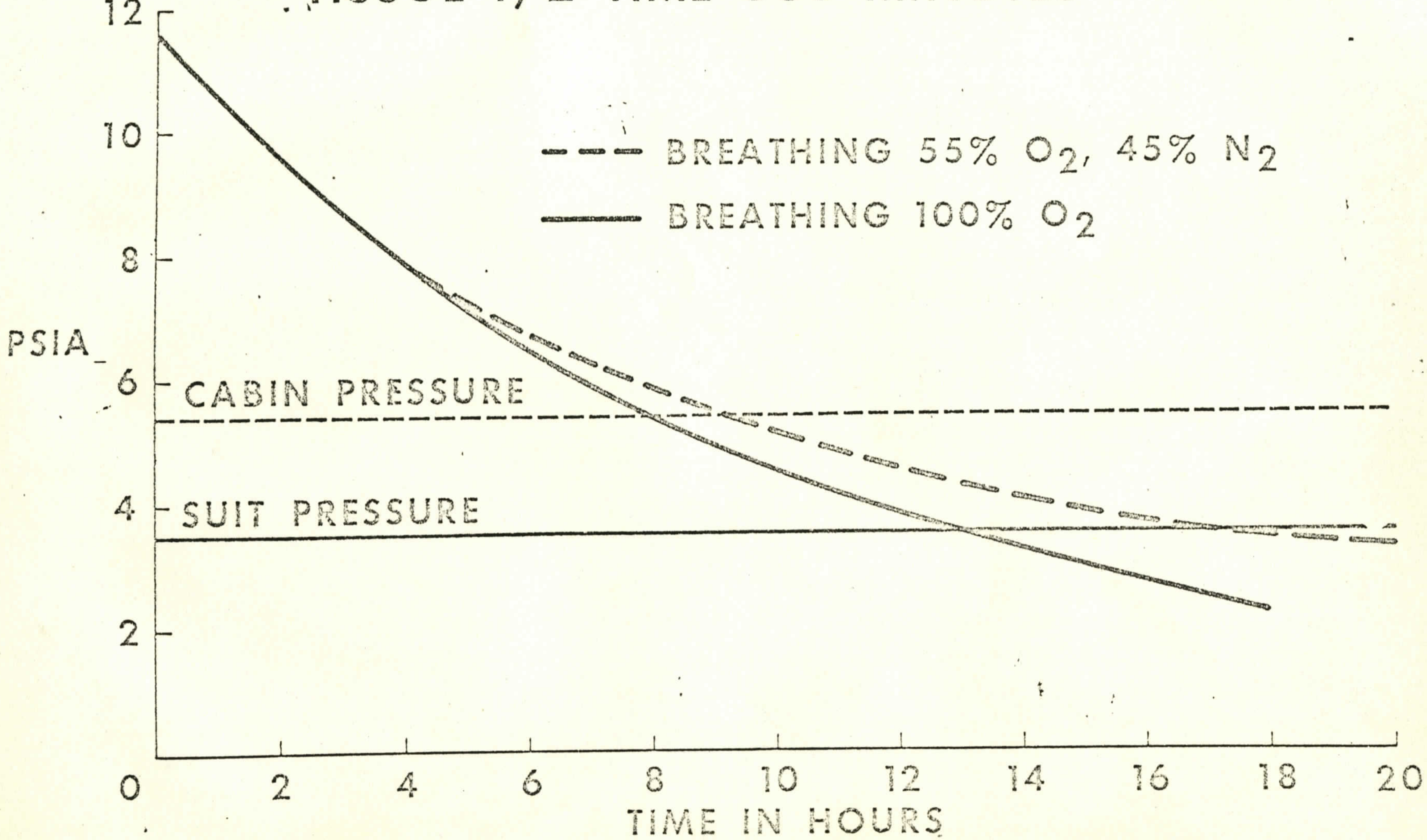
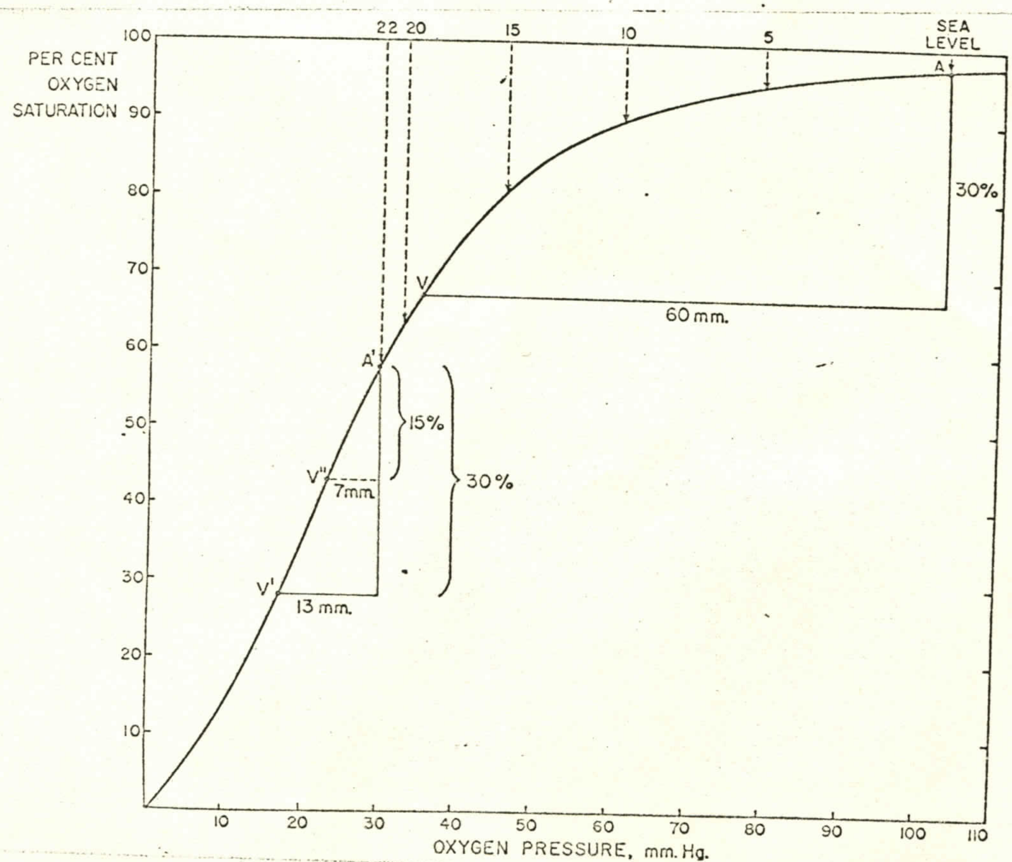


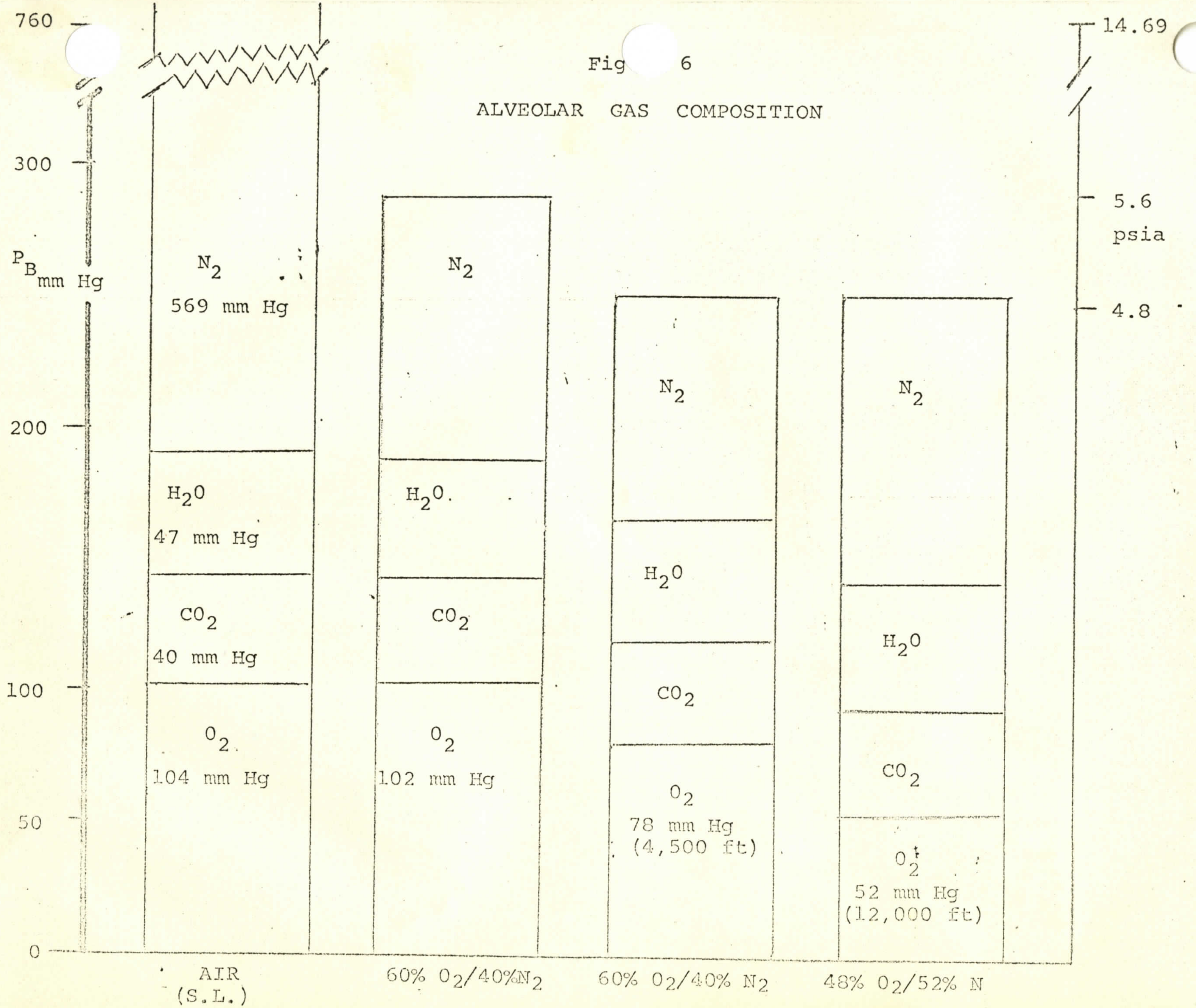
Figure 5



PER CENT OXYGEN SATURATION
100
90
80
70
60
50
40
30
20
10
22 20
15
10
5
SEA LEVEL
A
A'
V
V''
V'
30%
60 mm.
15%
30%
7mm.
13 mm.
10 20 30 40 50 60 70 80 90 100 110
OXYGEN PRESSURE, mm. Hg.

Fig 6

ALVEOLAR GAS COMPOSITION



Attachment 1

SUMMARY OF PERTINENT DECOMPRESSION PROTECTION DATA

The work reported herein was conducted at the following installations under NASA Defense Purchase Requests:

Aerospace Crew Equipment Laboratory
Philadelphia, Pennsylvania

School of Aerospace Medicine
Brooks AFB, Texas

Condition 1

2 hours preoxygenation at sea level followed by decompression to 35,000 feet and remaining there for 3 hours engaging in light exercise.

36 man exposures
18 completed
30 symptoms
18 forced descents

Condition 2

Same as above but with 3 hours preoxygenation at sea level.

44 man exposures
37 completed
9 symptoms
7 forced descents

Condition 3

2 hours preoxygenation at sea level followed by 9 hours on 100% O_2 at 5 psia, then decompressed to 35,000 feet for 3 hours breathing 100% oxygen and engaging in light exercise.

32 man exposures
27 completed
9 symptoms
5 forced descents

Condition 4

Same as above but with 3 hours duration at 5 psia breathing 100% O_2

26 man exposures
17 completed
15 symptoms
9 forced descents

Condition 5

3 hours preoxygenation at sea level followed by 3 hours on 100% O_2 at 5 psia, then decompressed to 35,000 feet for 3 hours breathing 100% oxygen and engaging in light exercise.

8 man exposures
8 completed
2 symptoms

Condition 6

2 hours preoxygenation at sea level followed by 9 hours at 5 psia breathing a 70% O_2 - 30% N_2 mixture then decompressed to 35,000 feet for 3 hours breathing oxygen and engaging in light exercise.

37 man exposures
14 completed
27 symptoms
23 forced descents