

**Naval Submarine Medical Research Laboratory**  
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**THE MEDICAL HAZARDS OF FLAME-SUPPRESSANT ATMOSPHERES**

*by*

*Douglas R. Knight*

Released by:  
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Commanding Officer  
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## SUMMARY PAGE

### PROBLEM

Most chamber fires can be suppressed or extinguished by reducing the concentration of oxygen in chamber air. Unfortunately, the reduction of O<sub>2</sub> concentration may be harmful to crews living inside the chamber. Few publications, if any, present a systematic evaluation of the medical hazards of flame-suppressant atmospheres.

### APPROACH

A significant reduction of flame-spread is defined by plotting isopleths of combustion activity on O<sub>2</sub>% – P<sub>O<sub>2</sub></sub> graphs. The graphs are used to define all possible modifications of air that suppress flames. Then, each modified atmosphere is evaluated for known medical hazards. By definition, there is no medical hazard in the atmosphere when the occupants are comfortable, able to work productively, and safe from short-or long-term health problems.

### FINDINGS

The following modifications of sea-level air will suppress combustion: 1. SUPPLEMENTATION - the addition of an appropriate foreign gas to air. 2. N<sub>2</sub> PRESSURIZATION - the addition of compressed N<sub>2</sub> to air. 3. DEPRESSURIZATION - the partial evacuation of air from the chamber. 4. N<sub>2</sub> DILUTION - the partial replacement of O<sub>2</sub> by N<sub>2</sub>. One or more of the following medical problems may be induced by the modified atmospheres; barotrauma, N<sub>2</sub> narcosis, decompression sickness, hypoxia, and inhalation toxicity. SUPPLEMENTATION is not recommended at this time due to potential risk of toxic inhalation. A review of experimental data suggests that N<sub>2</sub> DILUTION and N<sub>2</sub> PRESSURIZATION may be combined at minimal hazard to the crews serving aboard patrolling submarines. Novel atmospheres should be thoroughly evaluated for unknown medical hazards.

## ADMINISTRATIVE INFORMATION

This work was carried out under Naval Medical Research and Development Command Work Unit #MR00001.MR000101-5103. It was submitted for review on 23 October 1989; approved for publication on 19 April 1991, and assigned as NSMRL Report 1167.

## ABSTRACT

Flames are a potential hazard to the occupants of sealed chambers. This report describes four modifications of air that will suppress or extinguish flames. They are: 1. SUPPLEMENTATION - the addition of an appropriate foreign gas to air. 2. N<sub>2</sub> PRESSURIZATION - the addition of compressed N<sub>2</sub> to air. 3. DEPRESSURIZATION - the partial evacuation of air from the chamber. 4. N<sub>2</sub> DILUTION - the exchange of N<sub>2</sub> for O<sub>2</sub>. The primary medical hazards of flame-suppressant atmospheres are barotrauma, N<sub>2</sub> narcosis, decompression sickness, hypoxia, and inhalation toxicity. Experimental evidence supports the use of N<sub>2</sub> DILUTION to suppress flames aboard patrolling submarines. One or more of the following adjuncts may enhance the use of N<sub>2</sub> DILUTION without impairing human health: Physiological adaptation to hypoxia, addition of CO<sub>2</sub> to the atmosphere, and N<sub>2</sub> PRESSURIZATION.

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FLAMES

Flame Hazards

Accidental ignitions of combustible materials can quickly injure or kill the inhabitants of sealed chambers (Matthews, 1989; Press, 1988; Galasyn & Markham, 1969). Flames are likely to burn trapped victims when the configuration of the cabin accelerates heating of the internal environment. Figure 1 shows two profiles of air temperature, depending on whether the chamber is sealed (closed-hatch condition) or open to the outside air (open-hatch condition). The fire was ignited in a pool of butane and the flames spread upward to polyvinylchloride nitrile rubber hull insulation coated with intumescent paint. The closed-hatch condition accelerated the rise of air temperature inside the

chamber, indicating that sealing a chamber can reduce the effective time of fire fighting (Alexander, Bogan, Brandow, Carhart, Eaton, et al., 1985).

The failure of fire fighters to stop the spread of flames leads to smoke inhalation or burn injury, a fact illustrated by disastrous fires in O<sub>2</sub>-rich atmospheres. Figure 2 summarizes several case reports of injuries or deaths caused by flames in either space cabin simulators (75-100% O<sub>2</sub>) or hyperbaric chambers (25-50% O<sub>2</sub>). The accidents occurred in atmospheres containing higher P<sub>O<sub>2</sub></sub>'s than the sea-level value of approximately 160 torr. Five of nine deaths resulted from flashover and the few survivors were seriously burned. Most of the fires were ignited by malfunctioning electri-

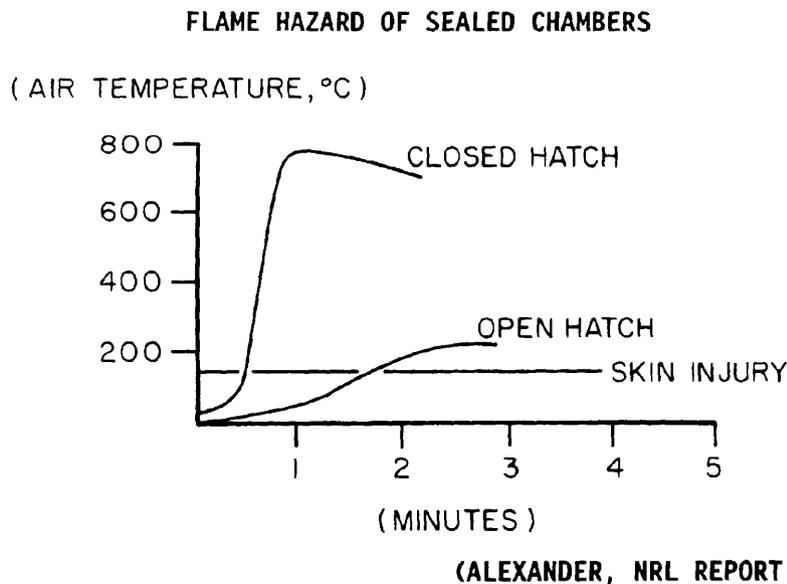


Fig. 1. FLAME HAZARD OF SEALED CHAMBERS. Two curves show the changes of air temperature when equal amounts of butane are burned inside a chamber that is either sealed (close hatch) or open (open hatch). Skin-burns occur when air temperatures rise above the horizontal line.

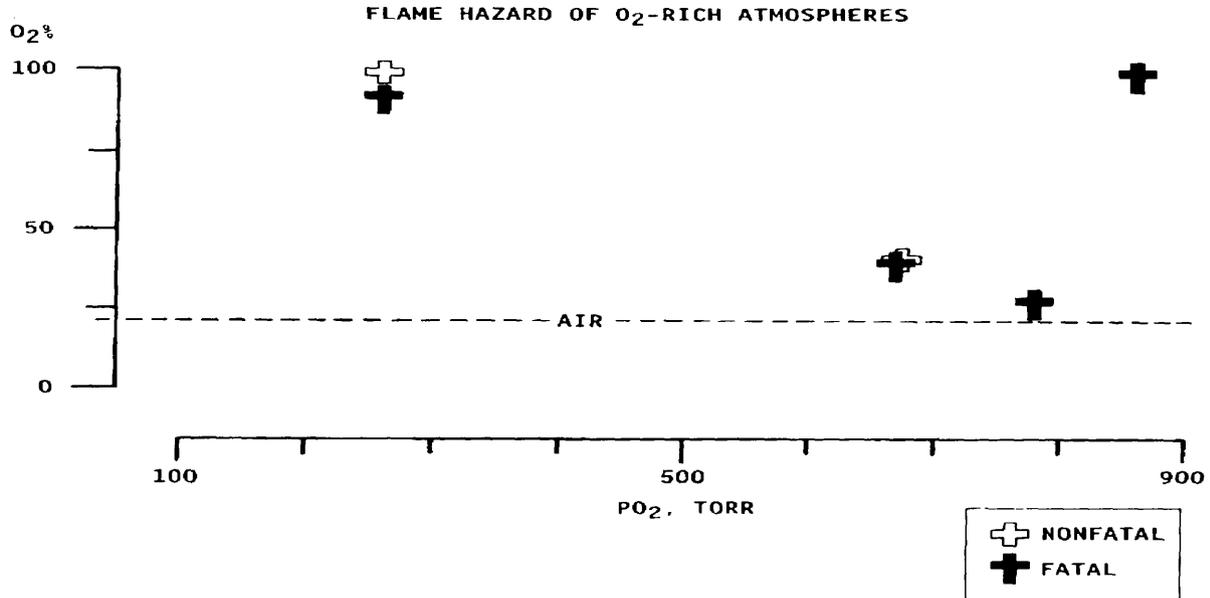


Fig. 2. FLAME HAZARD OF O<sub>2</sub>-RICH ATMOSPHERES. Symbols define the P<sub>O<sub>2</sub></sub> and O<sub>2</sub> concentrations of chamber atmospheres in which fires caused injuries or deaths.

cal equipment (Huggett, 1969; Galasyn & Markham, 1969; Harter, 1967).

#### Flammability Studies

According to Cook, Meirer, & Shields (1967), the behavior of combustion processes in N<sub>2</sub>-O<sub>2</sub> atmospheres varies according to the O<sub>2</sub>% and the gas pressures. The addition of O<sub>2</sub> to a pressurizable chamber raises the O<sub>2</sub>% without changing the P<sub>N<sub>2</sub></sub>. The resultant atmosphere lowers the ignition temperature and raises the burning rate of solid materials. Chamber pressurization with a N<sub>2</sub>-O<sub>2</sub> mixture of fixed composition increases the P<sub>O<sub>2</sub></sub> without changing the O<sub>2</sub>%. This also lowers the ignition temperature and raises the burning rate of solids. Increasing the O<sub>2</sub>% without changing the P<sub>O<sub>2</sub></sub> serves to increase the burning rate of cloth (Cook, Meirer, & Shields, 1967).

Since the behavior of combustion processes in N<sub>2</sub>-O<sub>2</sub> atmospheres varies

according to the O<sub>2</sub>% and gas pressures, the relative effects of O<sub>2</sub>%, P<sub>O<sub>2</sub></sub>, and P<sub>N<sub>2</sub></sub> on flammability can be analyzed by plotting isopleths of combustion activity on O<sub>2</sub>% - P<sub>O<sub>2</sub></sub> graphs. The O<sub>2</sub>% (Y axis) is functionally related to P<sub>O<sub>2</sub></sub> (X axis) by equation 1,

$$O_2\% = (100 / P_B)P_{O_2} \quad (1)$$

which conforms to the general equation for a straight line. The slope of the line, 100/P<sub>B</sub>, intersects the X axis at 0.

The barometric pressure is the sum of the partial pressures (equation 2).

$$P_B = P_{O_2} + P_{N_2} + P_{AOG} \quad (2)$$

The P<sub>N<sub>2</sub></sub> is derived in equations 3 and 4, which are used later in this paper to analyze the effects of the hyperbaric atmosphere on human health and performance.

$$N_2\% = 100 - O_2\% - AOG\% \quad (3)$$

$$P_{N_2} = (P_B / 100)N_2\% \quad (4)$$

The data in Figure 3 are burn-times for strips of filter paper. The lower burn-times indicate more rapid rates of complete combustion (Simons & Archibald, 1958) and the undefined burn-times indicate incomplete combustion (Kimzey, 1986; Cook, Dorr, & Shields, 1968). The undefined burn times (denoted by "X") are connected by a visual best-fit curve to identify the highest  $O_2\%$ 's for incomplete combustion. The range of  $O_2\%$ 's for incomplete combustion decreases toward an asymptotic value of about 14% when the  $P_{O_2}$  is increased above a minimum value of 25 torr. Above this

range is the zone of  $O_2\%$ 's which support complete combustion. At a constant  $P_{O_2}$  in the zone of complete combustion, the burn rate is reduced by lowering the  $O_2\%$  (Figure 3).

### Flame Suppression

Air can be converted to a flame-suppressant atmosphere by lowering the  $P_{O_2}$ , raising the  $P_{N_2}$ , or adding the appropriate foreign gas. The arrows of Figure 4 illustrate three different modifications of air that produce the zone of incomplete combustion as defined in Figure 3. Arrow "A" (Figure 4) represents the process of  $N_2$  PRESSURIZATION in which the well-mixed atmosphere is pressurized with nitrogen until the  $O_2$  concentration is reduced to

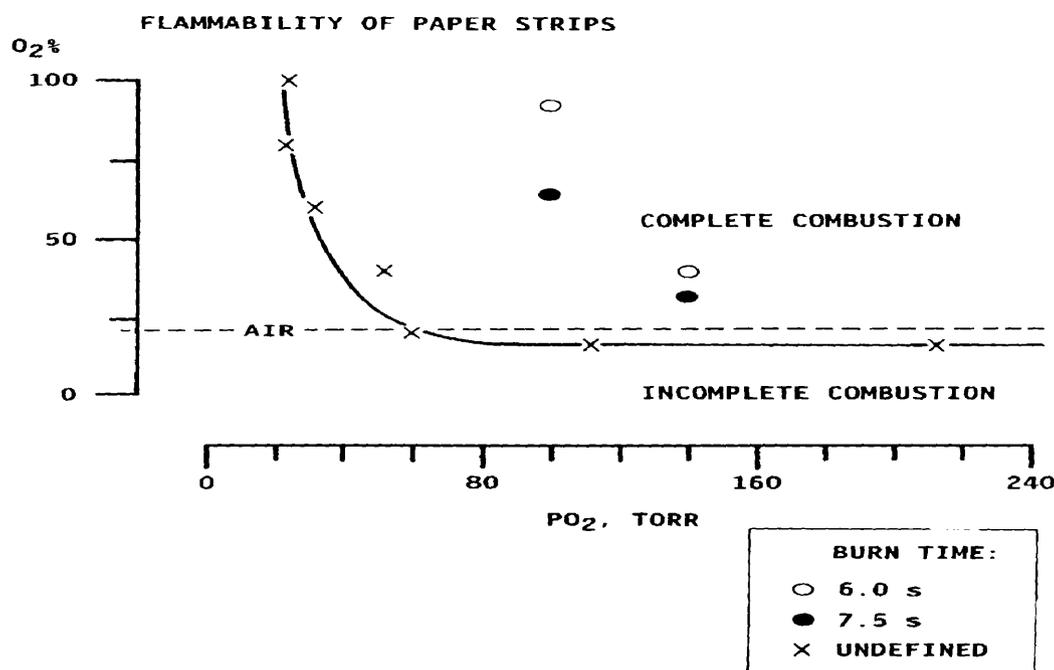


Fig. 3. FLAMMABILITY OF PAPER STRIPS. The position of the symbols defines the  $P_{O_2}$ 's and  $O_2$  concentrations of experimental atmospheres. Each symbol represents the burn time of paper strips (see INSET). "Undefined" burn time refers to the incomplete combustion of paper strips. Atmospheres on or below the curve do not support the complete combustion of paper strips.

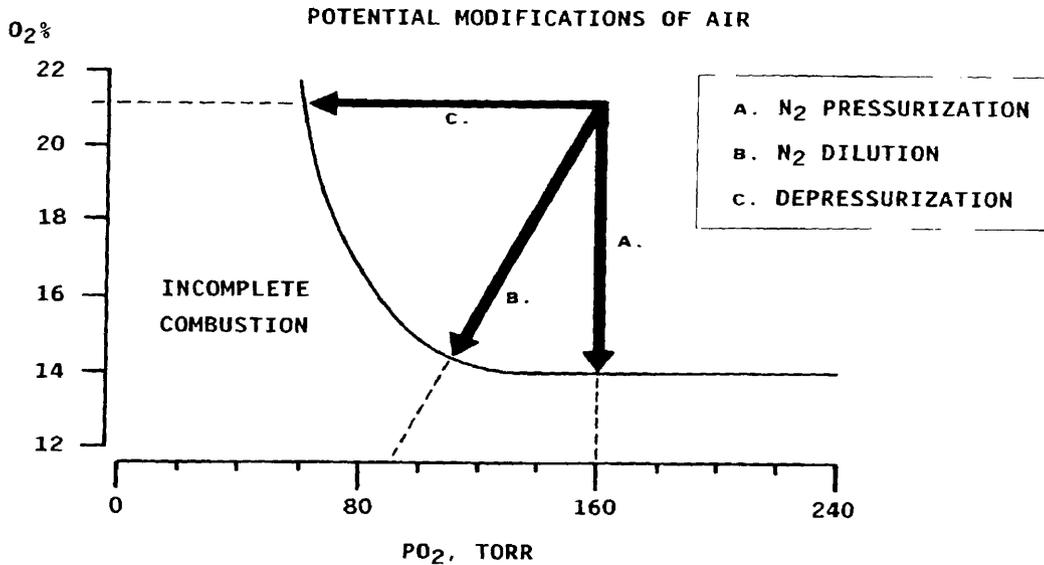


Fig. 4. POTENTIAL MODIFICATIONS OF AIR. Three solid arrows represent unique modifications (see INSET) of sea level air that produce a flame suppressant atmosphere. Atmospheric conditions on or below the curve do not support the complete combustion of paper strips.

14%. The  $P_B$  is increased by this procedure. Elevation of the  $P_{N_2}$  at a constant  $P_{O_2}$  interferes with flame propagation by lowering the temperature of the flame, reducing the gradient for diffusion of  $O_2$  into the flame, and introducing a third body into the recombination reactions of combustion (Tatem, Gann, & Carhart, 1974; Shilling, Werts, & Schandelmeier, 1976).

Arrow "B" (Figure 4) illustrates the process of  $N_2$  DILUTION in which  $N_2$  is exchanged for  $O_2$  until the  $O_2$  concentration is reduced to approximately 14.5% at normobaric pressure. The  $P_{O_2}$  is reduced by this procedure in direct proportion to the decrement of  $O_2\%$ . Carhart (1987) believes that reducing the  $O_2$  concentration below 19% will effectively slow the growth of fires.

Arrow "C" (Figure 4) depicts the use of atmospheric DEPRESSURIZATION

to reduce the  $P_{O_2}$  without changing the  $O_2$  concentration (Roth, 1964; Simons & Archibald, 1958). The  $P_B$  is decreased by this procedure.

A fourth modification of air, called SUPPLEMENTATION, utilizes the addition of a foreign gas to either drop the temperature of the flame or inhibit the recombination reactions of combustion (Huggett, 1969). A class of halocarbon gases extinguishes flames very effectively at the expense of decomposing into toxic gases which are difficult to remove from the atmosphere of a sealed chamber. Fluorocarbon gases are reported to be non-toxic to animals and might be useful for preventing flames if found to be safe for human exposure (McHale, 1972).

Assuming that the incomplete combustion of paper strips predicts a significant improvement of fire safety, it is

important to ask the question, "Can people inhabit these modified atmospheres without experiencing discomfort, illness, or impairment of their industrial productivity?" The remainder of this paper will address the primary medical guidelines for modifying the  $O_2\%$ ,  $P_{O_2}$ , and  $P_{N_2}$ .

## PRIMARY MEDICAL HAZARDS

The modifications of air necessary to suppress flames also have the potential for injuring the human body. The injuries of primary concern are toxic inhalation, barotrauma,  $N_2$  narcosis, decompression sickness, and hypoxia (Table 1).

### Supplementation Hazards.

Toxic inhalation is a primary hazard of foreign gases that will not be discussed in this report.

### $N_2$ Pressurization Hazards.

The increase of  $P_B$  is transmitted into gas pockets of the sinuses and middle

ears through channels that communicate with the human airway. Blockage of one of these channels prevents the transmission of atmospheric pressure into the gas pocket, thus establishing a pressure differential between the gas pocket and the atmosphere. For example, Figure 5A illustrates the middle ear as a gas pocket encased by hard bone (cross hatched area) and connected to the main airway by the Eustachian tube. Blockage of the Eustachian tube obstructs venting of the middle ear to atmospheric pressure, thereby preventing the equalization of gas pressures acting on the inner and outer surfaces of the flexible eardrum. The eardrum is stretched toward the side of lower pressure in relation to the pressure differential between the atmosphere and middle ear (Figure 5B). Ear pain begins at pressure differentials  $\leq 60$  torr and increases with higher pressures until differentials of 100-500 torr rupture the ear drum (Armstrong & Heim, 1937). Damage of the eardrum is an example of barotrauma, which is the injury of tissues caused by pressure differentials.

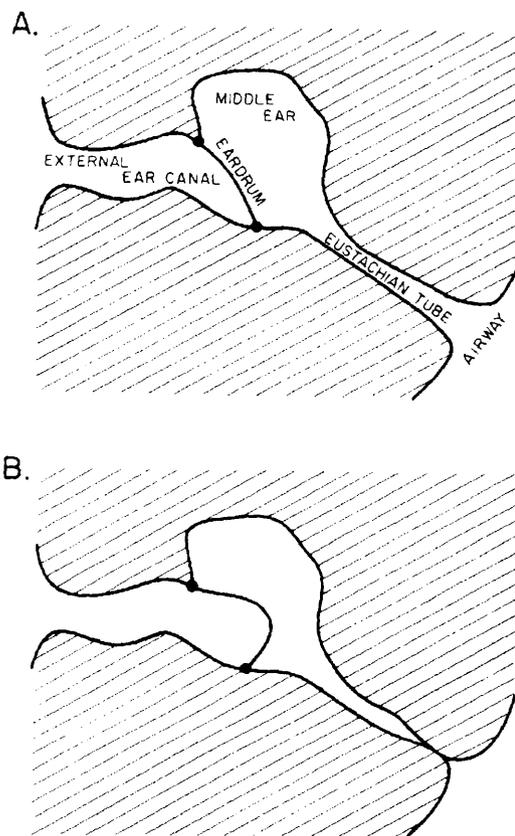
Table 1.

MEDICAL GUIDELINES		
<u>MODIFICATION PROCEDURE</u>	<u>PRESSURE CHANGE</u>	<u>GUIDELINES</u>
$N_2$ DILUTION	▼ $p_{O_2}$	Hypoxia
$N_2$ PRESSURIZATION	▲ $P_B$	Barotrauma
	▲ $p_{N_2}$	$N_2$ Narcosis
	eventual ▼ $P_B$	Barotrauma, Decompression sickness, Hypoxia
DEPRESSURIZATION	▼ $p_{O_2}$	Hypoxia
	▼ $P_B$	Barotrauma, Decompression sickness
	eventual ▲ $P_B$	Barotrauma

Chemists refer to  $N_2$  as an inert gas, but pressurized  $N_2$  is not inert when absorbed to excess amounts by biological systems. Figure 6 shows isobars of  $P_{N_2}$  that intersect compressed air at points A-C.  $N_2$  narcosis can result from exposure to compressed air at point A, where the  $P_{N_2} = 2420$  torr. Assuming that compressed  $N_2$  is the sole cause of  $N_2$  narcosis (p 175 of Shilling, Werts, & Schandelmeier, 1976) and not some other factor such as the accumulation of  $CO_2$  in tissues, then  $N_2$  pressurization of air to point D would induce a state of narcosis equivalent to that of exposure to compressed air at point A. The narcosis is reversible by lowering the  $P_{N_2}$ .

Decompression sickness (DCS) occurs when rapid depressurization of the atmosphere induces  $N_2$ -rich bubbles to grow in the tissues or blood stream (Shilling, Werts, & Schandelmeier, 1976). The risk of DCS exists when the ratio of tissue  $P_{N_2}$  / ambient  $P_B$  exceeds a value of 1.0, in which case the depressurization of an occupied atmosphere may need to be interrupted or slowed to prevent symptoms and injury (Behnke, 1967). There are published tables of pressure-time schedules which prescribe an acceptable decompression from hyperbaric atmospheres (U.S. Navy Diving Manual).

Figure 6 shows air pressures which predispose humans to DCS at exposure times of 0.5 h (point A), 1 h (point B), and 48 h (point C). Weathersby, Hart, Flynn, & Walker, (1987) suggest that only the inert gas need be considered in calculating human decompression schedules which therefore permits the



ADAPTED FROM (BILLINGS, 1973; NASA SP-3006)

**Fig. 5. BAROTRAUMA OF THE MIDDLE EAR.** Bone (cross-hatching) completely surrounds gas-filled spaces of the ear. Graph A shows the position of the eardrum when there is no pressure difference between the external and middle ear cavities. Graph B shows inward distension of the eardrum produced by higher pressure in the external ear canal. Soft- or hard tissue blockage of the eustachean inlet prevented the equalization of pressures across the eardrum.

assumption that the same risk of DCS exists anywhere along the  $P_{N_2}$  isobars of Figure 6 when the atmosphere is decompressed to sea level air. Therefore, each  $P_{N_2}$  isobar predisposes humans to DCS at the same exposure times used for the intercepts with 21%  $O_2$ . Note that the isobar for  $P_{N_2} = 1140$  crosses the 160 torr coordinate of the X axis at point E, where the  $O_2\%$  is 12.3. The  $P_{N_2}$  isobars of Figure 6 are not true

threshold values for DCS and N<sub>2</sub> narcosis, but serve to warn of the risks (which are yet to be defined).

Eckenhoff, Osborne, Parker, & Bondi (1986) reported no incidence of DCS after 48 h exposures to 1064 torr N<sub>2</sub> in compressed air suggesting that limiting the N<sub>2</sub> pressurization to P<sub>N<sub>2</sub></sub>'s < 1064 torr avoids the risk of DCS upon returning to sea-level air. This P<sub>N<sub>2</sub></sub> would cross the 160 torr coordinate of the X axis at an O<sub>2</sub>% of 13.1 (Figure 6). Unfortunately, the variability of human responses to hyperbaric environments may mean that some people are at risk for symptoms of DCS after 48 h exposures to P<sub>N<sub>2</sub></sub> < 1064 torr.

O<sub>2</sub> is absorbed by body fluids and binds to heme pigments in all cells. O<sub>2</sub> transport to the cells is driven by gradients of P<sub>O<sub>2</sub></sub> that exist between the atmosphere and the cellular fluids. Oxygen may damage the lung when the P<sub>O<sub>2</sub></sub> exceeds 380 torr (Shilling, Werts, & Schandelmeier, 1976), so it is important to emphasize that N<sub>2</sub> pressurization does not change the P<sub>O<sub>2</sub></sub> in a sealed chamber. Therefore, pulmonary oxygen toxicity is not a primary medical concern of N<sub>2</sub> pressurization.

Flame extinction by rapid N<sub>2</sub> PRESSURIZATION has been successfully tested on laboratory animals (Dressler, Robinson, Gann, Stone, Willimas, et al., 1977). N<sub>2</sub> PRESSURIZATION to 6% O<sub>2</sub>

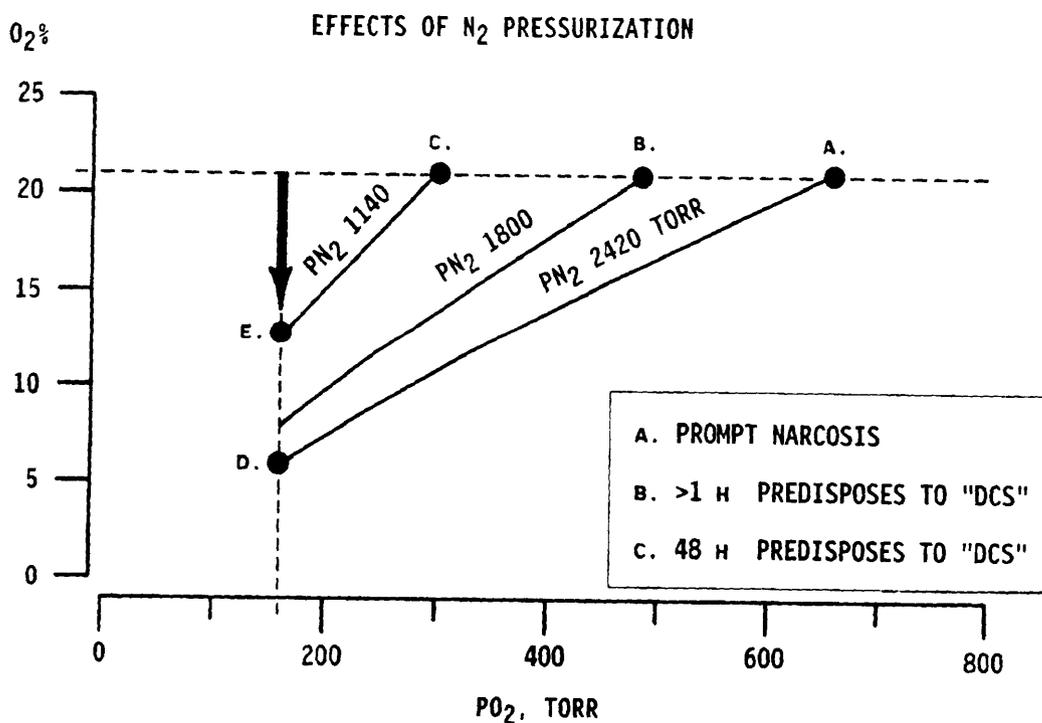


Fig. 6. EFFECTS OF N<sub>2</sub> PRESSURIZATION. A solid arrow represents the N<sub>2</sub> pressurization of sea level air. Three solid curves are N<sub>2</sub> isobars that produce narcosis or predispose humans to decompression sickness (see INSET) in hyperbaric atmospheres. Specific points on the graph are discussed in the text.

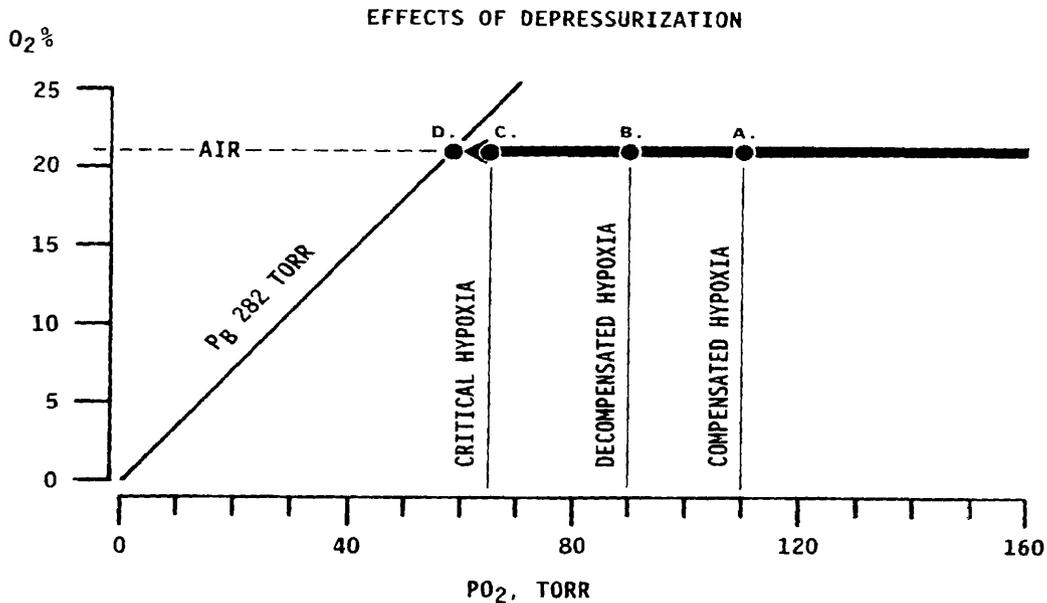


Fig. 7. EFFECTS OF DEPRESSURIZATION. A solid arrow represents the depressurization of sea level air to an isobar of hypobaric pressure. Three vertical isobars of  $O_2$  represent thresholds to progressively severe hypoxia in unacclimatized humans.

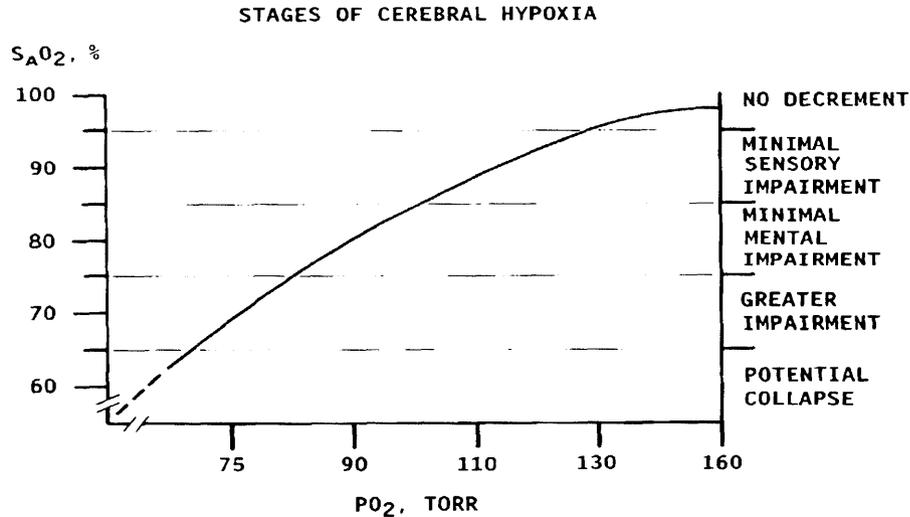
creates an atmospheric zone of noncombustion (Cook, Dorr, & Shields, 1968), but human use of the zone is infrequent. There is a case report of unpleasant symptoms in humans exposed to 3%  $O_2$  by  $N_2$  PRESSURIZATION, but the cause of symptoms in this extreme environment has not been determined (Moeller, 1975).

Rapid decompression of the pressurized atmosphere introduces the risk of barotrauma to the lung. Overinflation of lung tissue occurs when obstruction of an airway prevents alveolar gas from escaping to the relatively lower pressure of the atmosphere. The rupture of alveoli is likely to occur when intrapulmonary pressure exceeds atmospheric pressure by 80 torr (Shilling, Werts, & Schandelmeier, 1976; Billings, 1973A). The subsequent leakage of air into tissues causes at least one of the following medical disorders; mediastinal em-

physema, pulmonary interstitial emphysema, air embolism, and pneumothorax. Life is threatened by these conditions when there is reduction of the cardiac output, collapse of the lung, or flow of bubbles into coronary arteries and vessels of the brain (Waite, Mazzone, Greenwood, & Larsen, 1967).

#### Depressurization Hazards

The physiological effects of depressurization are documented in numerous studies of mountaineers and aviators. One effect, hypoxia, is known to impair the individual's physical and mental function due to reduction of the  $PO_2$ . Points A-C of Figure 7 represent the threshold  $PO_2$ 's between four phases of acute hypoxia as defined by the investigative work of Strughold (Randel, 1971). Point A illustrates the transition from an "indifferent" phase of hypoxia to "compensated" hypoxia when the  $PO_2$



(McFARLAND, ANN NY ACAD SCI, 1970)

Fig. 8. STAGES OF CEREBRAL HYPOXIA. A visual best-fit curve is drawn through the scatterplot of data published by McFarland (1970). Percentage saturation of arterial

is below 110 torr. According to Strughold's classification, the "indifferent" phase of depressurization does not impair human function. "Compensated" hypoxia stimulates the cardiorespiratory system, thus assisting the transport of O<sub>2</sub> in resting individuals. However, decompensation occurs when there is an additional exposure to heat or the performance of exercise. The transition from "compensated" to "decompensated" hypoxia occurs at the P<sub>O<sub>2</sub></sub> of 90 torr (point B, Figure 7). During "decompensated" hypoxia (also referred to as "incomplete compensation") the cardiorespiratory system does not prevent deterioration of physical and mental performance. A "critical" phase of hypoxia develops when the P<sub>O<sub>2</sub></sub> falls below 65 torr (point C, Figure 7). "Critical" hypoxia can severely degrade human performance and cause unconsciousness. A lethal threshold for hypoxia is believed to exist near point D of Figure 7 (Randel, 1971).

Strughold's thresholds (ie, points A-C Figure 7) warn of the hazard of hypoxia, but it is wrong to interpret the thresholds as well defined changes in physiological function that equally apply to all persons. People differ in their tolerances of hypoxia, as indicated by published frequency distributions of P<sub>O<sub>2</sub></sub>'s known to impair the health of exposed populations (Randel, 1971).

There are conflicting opinions about the minimum P<sub>O<sub>2</sub></sub> at which healthy persons can sustain their work performance. Residents live and work in cities at low altitude where task performance is apparently not impaired by hypoxia. For example, air traffic controllers successfully manage the congested air traffic at Denver's airport (P<sub>O<sub>2</sub></sub> = 130 torr) without breathing supplemental oxygen. As residents, they have adapted to low altitude by increasing their red blood cell volumes (Knight, 1985). McFarland (1970) studied human cerebral

function at altitude and in sea-level atmospheres of lowered O<sub>2</sub>%. His findings, and those of other investigators, are summarized in a plot of the S<sub>a</sub>O<sub>2</sub> as a function of altitude. Figure 8 is an adaptation of McFarland's plot in which the X axis is converted from units of altitude to units of P<sub>O<sub>2</sub></sub>. The curve is intersected by a zone of minimal sensory impairment at P<sub>O<sub>2</sub></sub>'s of 100-130 torr. The existence of this zone is supported by published reports of impaired visual adaptation to the dark and induced body sway at P<sub>O<sub>2</sub></sub>'s of 120-130 torr (McFarland, 1971; Fraser, Eastman, Paul, & Porlier, 1987; Billings, 1973B; Randel, 1971). Whether or not the zone of minimal sensory impairment overlaps with degradation of task performance is a matter of controversy since investigators do not agree on the decrement of psychomotor performance at P<sub>O<sub>2</sub></sub>'s of 120-130 torr (Denison, Ledwith, & Poulton, 1966; Fowler, Paul, & Taysor, 1985). Figure 8 shows a zone of minimal impairment in mental function at P<sub>O<sub>2</sub></sub>'s of 100-85 torr and greater impairment at P<sub>O<sub>2</sub></sub>'s of 85-70 torr. Exposure to P<sub>O<sub>2</sub></sub> < 70 torr may cause the individual to collapse (McFarland, 1970). Based on Figure 8, it is reasonable to postulate that the minimum P<sub>O<sub>2</sub></sub> for unacclimatized humans is 130 torr, below which the risk for hypoxic impairment

of health or performance increases with the reduction of ambient P<sub>O<sub>2</sub></sub>.

Figure 8 does not identify the domains of P<sub>O<sub>2</sub></sub> causing insomnia (Pappenheimer, 1984), impairment of industrial productivity (Tichauer, 1963), reduction of maximum aerobic power (Billings, 1973B), symptoms of acute mountain sickness (Billings, 1973B; Johnson & Rock, 1988), or significant interactions of hypoxia with atmospheric contaminants<sup>1</sup>. It is therefore important to consider effects other than cerebral hypoxia when attempting to define the minimum P<sub>O<sub>2</sub></sub> for safe occupation of chambers.

Depressurization of the atmosphere may cause barotrauma and DCS, both of which were discussed as potential complications of N<sub>2</sub> PRESSURIZATION. DCS is known to occur when air is depressurized to P<sub>B</sub> = 282 torr (point D, Figure 7) and may occur at even less severe decreases of P<sub>B</sub> (U.S. Naval Flight Surgeon's Manual).

#### N<sub>2</sub> Dilution Hazard.

With this approach, there is no change of P<sub>B</sub> that could cause barotrauma, nor does the slight increase of P<sub>N<sub>2</sub></sub> produce narcosis. The effects of hypoxia from N<sub>2</sub> DILUTION are presumably equivalent to the effects of hypoxia from DEPRESSURIZATION

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[1] There are literally hundreds of inorganic and organic vapors that contaminate submarine atmospheres. The prevalent contaminant, CO<sub>2</sub>, exists at molar concentrations of approximately 1%.

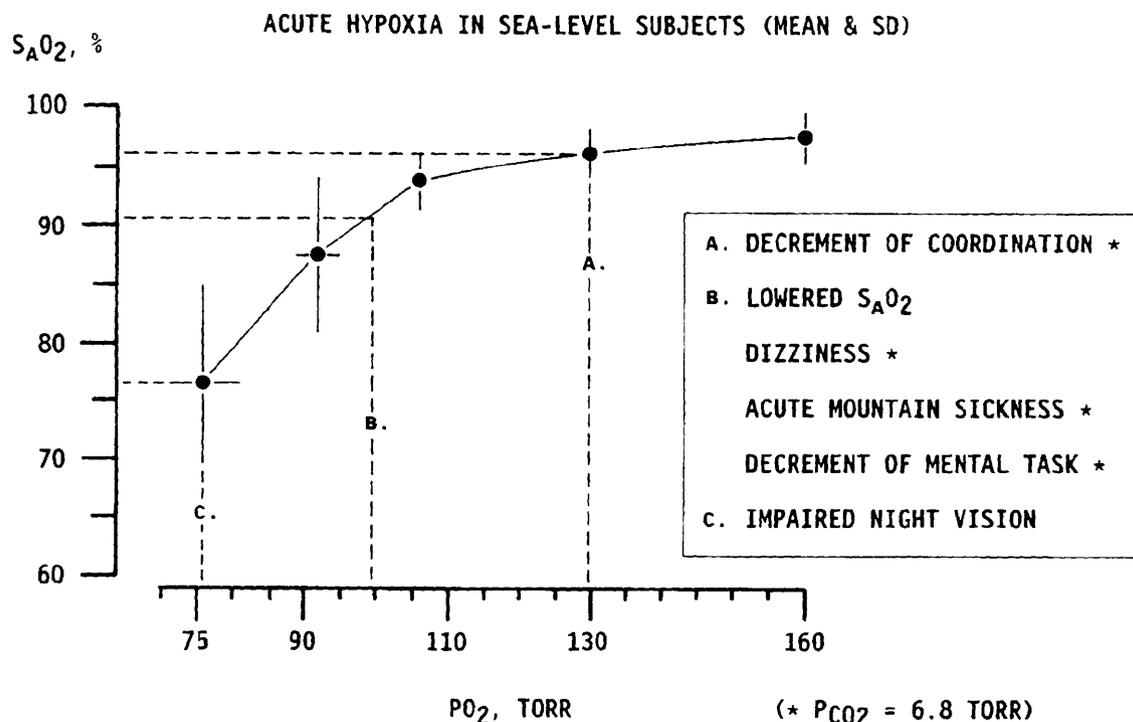


Fig. 9. ACUTE HYPOXIA IN SEA-LEVEL SUBJECTS. A visual best-fit curve is drawn through the mean values of experimental P<sub>O<sub>2</sub></sub>'s studied by the author and colleagues. The INSET describes significant medical and physiological conditions encountered at the specific isobars of O<sub>2</sub>. Axes were defined in the legend for figure 8.

when both atmospheres contain equivalent reductions of the P<sub>O<sub>2</sub></sub>.

### STUDIES OF HYPOXIA AT NORMOBARIC PRESSURE

Six experiments were performed by military scientists (see ACKNOWLEDGEMENTS) in which separate groups of volunteers<sup>2</sup> breathed 10%, 12%, 13%, or 17% O<sub>2</sub> without knowing the composition of the gas. The objective was to determine a minimum atmospheric P<sub>O<sub>2</sub></sub> that permits safe occupancy of chambers for periods of days. All sub-

jects were trained to perform one or more tasks of mental function before the experiment began and all completed a control experiment in 21% O<sub>2</sub>. Measurements were made of the S<sub>A</sub>O<sub>2</sub>, moods, symptoms of acute mountain sickness, mental function, muscular coordination, night vision, visual contrast sensitivity, and speech discrimination. The details of experimental design and data analysis have been reported by the various investigators (Knight, Luria, Socks, & Rogers, 1987; Luria & Knight, 1987; Marshall, 1987; Schlichting, Knight, & Cymerman, 1988; Shukitt,

[2] The nature and purpose of the studies and the risks involved were explained verbally and given on a written form to each subject prior to his voluntary consent to participate. The protocol and procedures for the studies were approved by the Committees for Protection of Human Subjects at the Naval Submarine Medical Research Laboratory, New London, CT and the U.S. Army Research Institute of Environmental Medicine, Natick, MA.

Burse, Banderet, Knight, & Cymerman, 1988; Luria & Morris, 1988).

Figure 9 illustrates the following:

The standard deviation bars illustrate the variability in  $S_aO_2$ 's of unacclimatized subjects exposed to various  $PO_2$ .

129 TORR  $O_2$  (17%  $O_2$ ):

The mean  $S_aO_2$  (97%) did not significantly differ from a mean control value of 98% and there were no changes of moods or symptoms of acute mountain sickness. The mental and visual performance tests were not degraded by 4-h exposures to uncontaminated gas mixtures. The 2.6-d exposure to 129 torr  $O_2$  was purposely contaminated with 6.8 torr  $CO_2$  in order to simulate the atmospheres existing aboard submarines<sup>[1]</sup>. One task of muscular coordination was slightly degraded during the first 4 h of the contaminated exposure, but this impairment of coordination did not degrade the subjects' performance of other tasks. The impairment disappeared with continuation of the exposure (Schlichting, Knight, & Cymerman, 1988).

99 TORR  $O_2$  (13%  $O_2$ )-6.8 torr  $CO_2$ -balance  $N_2$ :

There were transient bouts of impaired coordination and impaired mental function during the first 4 h of the 2.6 d exposure. These were followed later by the onset of dizziness. Forty percent of the subjects developed symptoms of acute mountain sickness by the

11th h. The incidence of mountain sickness and dizziness diminished in d 2 and all symptoms disappeared by d 2 of the recovery in 21%  $O_2$  (Shukitt, Burse, Banderet et al., 1988; Schlichting Knight, & Cymerman, 1988).

87-90 TORR  $O_2$  (12%  $O_2$ ):

A 2 h exposure reduced the mean  $S_aO_2$  to 80% without causing symptoms of hypoxia in resting subjects. This degree of hypoxia was not associated with changes of the visual function tests, speech discrimination, or the performance of an arithmetic task.

76 TORR  $O_2$  (10%  $O_2$ ):

A 10 min exposure reduced the mean  $S_aO_2$  to 77%, induced dizziness, and degraded the night vision. This was the only exposure to change any of the visual function tests (Luria & Knight, 1987).

The results indicate that muscle coordination and mental performance quickly acclimatize to hypoxia after reduction of the atmospheric  $PO_2$  to 130 torr. Therefore,  $N_2$  dilution may be used to reduce the  $O_2$  concentration to 17%. Further reduction of the  $PO_2$  to 100 torr induces symptoms of acute mountain sickness in unacclimatized people. Additional experimental work is needed to determine if exposures to 110-120 torr  $O_2$  produce symptoms of acute mountain sickness or transiently impair psychomotor performance.

## APPLICATIONS TO SUBMARINES.

Adjunct strategies may enhance the physiological tolerance of reduced O<sub>2</sub> concentrations produced by N<sub>2</sub> dilution. Physiological adaptation to hypoxia will abolish the discomfort of multiday exposures to 13% O<sub>2</sub> (P<sub>O<sub>2</sub></sub> 99 torr), as reported by Shukitt, Burse, Banderet, et al., (1989). Gradual use of N<sub>2</sub> DILUTION to reduce the O<sub>2</sub> concentration below 17% may avoid the discomfort of abrupt, multiday exposures to 13% O<sub>2</sub>. A second adjunct is the addition of a respiratory stimulant, CO<sub>2</sub>, to the atmosphere. CO<sub>2</sub> is known to enhance O<sub>2</sub> delivery to the tissues by stimulating ventilation, improving the release of O<sub>2</sub> from hemoglobin, and dilating blood vessels. Preliminary studies indicate that 13% O<sub>2</sub> - 3% CO<sub>2</sub> - balance N<sub>2</sub> does not degrade mental performance in resting subjects (Knight, Luria, Socks, et al., 1987). A third adjunct is the use of N<sub>2</sub> PRESSURIZATION to supplement N<sub>2</sub> DILUTION, as discussed in the following concluding paragraphs.

P <sub>O<sub>2</sub></sub> torr	Safe max P <sub>B</sub> (torr)	%O <sub>2</sub>
120	880	13.6
130	890	14.6
140	900	15.5

Huggett suggested that an atmosphere of 128 torr O<sub>2</sub>-balance 722 torr N<sub>2</sub> reduces the flame hazard of combustible materials by raising the heat capacity of the atmosphere. His reason for raising the P<sub>N<sub>2</sub></sub> to 722 torr was based on flame

suppression (Huggett, 1969). The subsequently proposed use of 130 torr O<sub>2</sub>-balance 870 torr N<sub>2</sub> (Knight, 1985) took into account the hazard of DCS in flame-suppressant atmospheres. More modest N<sub>2</sub> pressurization may provide safe atmospheres for a variety of human activities, particularly if DCS can be completely avoided by limiting the exposure to a maximum atmospheric P<sub>N<sub>2</sub></sub> of 760 torr (the tissue P<sub>N<sub>2</sub></sub> would not exceed 760 torr under these conditions). This is based on the theory that no risk for DCS exists when the ratio of tissue P<sub>N<sub>2</sub></sub> to ambient P<sub>B</sub> ≤ 1 (Behnke, 1967). In a binary gas mixture of N<sub>2</sub> and O<sub>2</sub>, a range of safe maximum P<sub>B</sub>'s can be computed as a function of the atmospheric P<sub>O<sub>2</sub></sub>. A sample range is shown in Table 2.

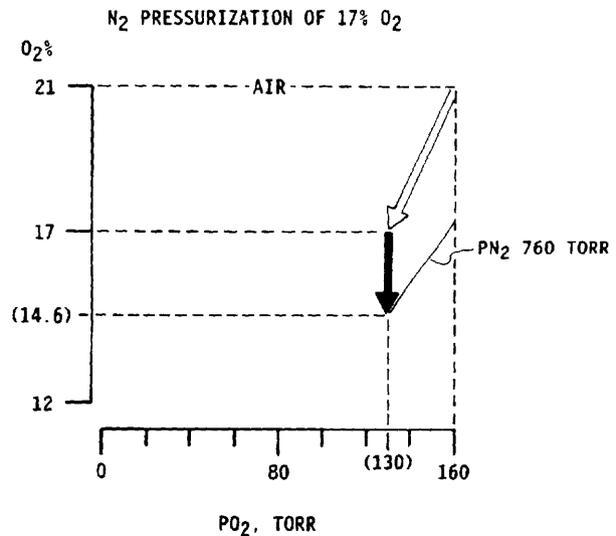


Fig. 10. N<sub>2</sub> PRESSURIZATION OF 17% O<sub>2</sub>. Sea level air is initially modified by N<sub>2</sub> dilution (open arrow) and further processed by N<sub>2</sub> pressurization (solid arrow). The solid curve is a N<sub>2</sub> isobar for 760 torr. Intercepts of the dashed lines are discussed in the test for Table 2.

Figure 10 presents a scheme for avoiding hypoxia and DCS during the occupation of a flame-suppressant atmosphere. The open arrow depicts the use of N<sub>2</sub> DILUTION to lower the O<sub>2</sub>% to 17, where the P<sub>O<sub>2</sub></sub> is 130 torr. Additional N<sub>2</sub> PRESSURIZATION is used for two reasons; (a) the O<sub>2</sub>% is lowered to 14.6 without changing the P<sub>O<sub>2</sub></sub> and (b), the atmosphere can be decompressed to P<sub>B</sub> - 760 torr without exposing crews to the hazard of DCS. The incidence of barotrauma can be minimized by using very slow rates of compression and decompression. Experimental support for the habitability of such an atmosphere comes from studies showing that subjects can safely breathe either 11% or 13% O<sub>2</sub> at P<sub>O<sub>2</sub></sub> = 130 torr for 4 h without hypoxemia or decrement of psychomotor performance (Knight, Luria, Socks, et al., 1987).

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The views expressed in this article are those of the author and do not reflect the official policy or position of the

Department of the Navy, Department of Defense, or the U.S. Government.

#### SYMBOLS

d	day.
h	hour.
O <sub>2</sub>	molecular oxygen.
O <sub>2</sub> %	The molar concentration of oxygen, expressed as a percentage of the gas mixture.
N <sub>2</sub>	molecular nitrogen.
P <sub>AOG</sub>	The combined partial pressures of gases other than oxygen and nitrogen in the atmosphere, expressed in units of torr.
P <sub>B</sub>	The barometric pressure, expressed in units of torr.
P <sub>N<sub>2</sub></sub>	The partial pressure of nitrogen, expressed in units of torr.
P <sub>O<sub>2</sub></sub>	The partial pressure of oxygen, expressed in units of torr.
s	seconds.
S <sub>a</sub> O <sub>2</sub>	The O <sub>2</sub> saturation of arterial hemoglobin, expressed as a percentage of complete saturation.

## DEFINITIONS

**Air:** 78% nitrogen, 20.9% oxygen, 0.9% argon, and additional gases in trace concentrations.

**Air embolism:** Bubbles of air that flow in the bloodstream until blocked by vessels of smaller caliber than the bubble diameters.

**Decompression sickness (DCS):** A group of illnesses characterized by formation of gas bubbles in blood or tissues, caused by release of physically dissolved gases when environmental pressure is decreased at sufficient rate and magnitude (Bartels, Dejours, Kellogg, & Mead; 1973).

**Flashover:** The sudden spread of flame over an area when it becomes heated to the flash point.

**Hypoxemia:** A state in which the oxygen pressure and/or concentration in arterial and/or venous blood is lower than its normal value at sea level (Bartels, et al.; 1973).

**Hypoxia:** A physiological state in which the amount of O<sub>2</sub> in the lung, blood, and/or tissues is abnormally low compared to that of normal resting man breathing air at sea level (Bartels, et al.; 1973).

**Hemoglobin:** The protein in red blood cells that transports 99% of the O<sub>2</sub> carried by the blood stream.

**Incomplete combustion:** The self extinction of a flame before there is complete burning of the test material (Cook, Meirer, & Shields, 1967).

**Mediastinal emphysema:** The accumulation of air in normally gas-free tissue spaces surrounding the heart, esophagus, and large blood vessels in the chest.

**N<sub>2</sub> narcosis:** Depression of brain function due to high partial pressure of nitrogen (Bartels, et al.; 1973).

**Normobaric pressure:** The barometric pressure of approximately 760 torr. The variation of normobaric pressure may be defined by the range of barometric pressures measured at sea-level.

**Oxygen saturation (S<sub>a</sub>O<sub>2</sub>):** The amount of oxygen combined with hemoglobin, expressed as a percentage of the O<sub>2</sub> capacity of that hemoglobin (Bartels, et al.; 1973).

**Pneumothorax:** The escape of air into the pleural space of the lung.

**Pulmonary oxygen toxicity:** The injury to lung tissue caused by exposure to P<sub>O<sub>2</sub></sub> ≥ torr. The degree of injury can progress to an irreversible stage depending on the level of P<sub>O<sub>2</sub></sub> and duration of exposure (Shilling, Werts, & Schandelmeier, 1976).

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