Naval Submarine Medical Research Laboratory

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THE MEDICAL HAZARDS OF FLAME-SUPPRESSANT ATMOSPHERES

by

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Released by:
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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_2 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 $O_2\% - P_{O_2}$ 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_2 PRESSURIZATION - the addition of compressed N_2 to air. 3. DEPRESSURIZATION - the partial evacuation of air from the chamber. 4. N_2 DILUTION - the partial replacement of O_2 by N_2. One or more of the following medical problems may be induced by the modified atmospheres; barotrauma, N_2 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_2 DILUTION and N_2 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_2 PRESSURIZATION - the addition of compressed N_2 to air. 3. DEPRESSURIZATION - the partial evacuation of air from the chamber. 4. N_2 DILUTION - the exchange of N_2 for O_2. The primary medical hazards of flame-suppressant atmospheres are barotrauma, N_2 narcosis, decompression sickness, hypoxia, and inhalation toxicity. Experimental evidence supports the use of N_2 DILUTION to suppress flames aboard patrolling submarines. One or more of the following adjuncts may enhance the use of N_2 DILUTION without impairing human health: Physiological adaptation to hypoxia, addition of CO_2 to the atmosphere, and N_2 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_2-rich atmospheres. Figure 2 summarizes several case reports of injuries or deaths caused by flames in either space cabin simulators (75-100% O_2) or hyperbaric chambers (25-50% O_2). The accidents occurred in atmospheres containing higher P_{O_2}'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-

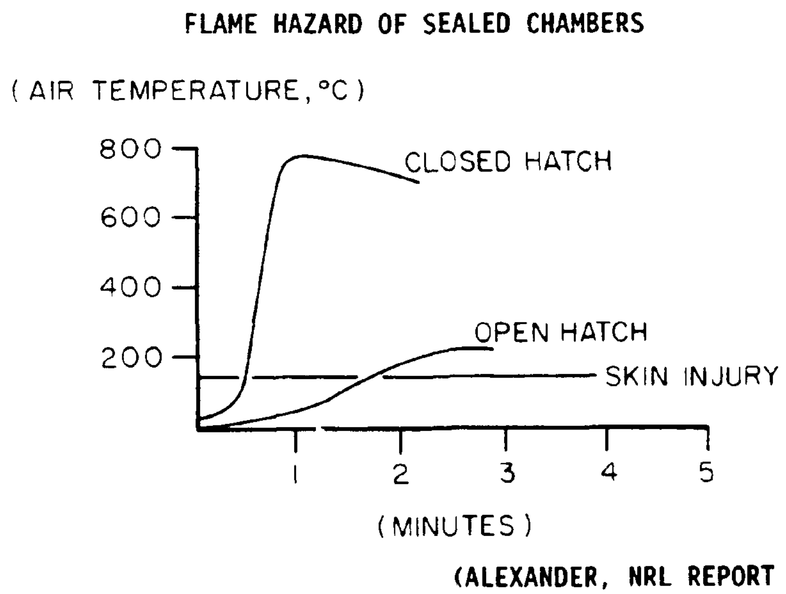

Fig. 1. FLAME HAZARD OF SEALED CHAMBERS. Two curves show the changes of air temperature when equal amounts of butane are burned inside a chamber that is either sealed (close hatch) or open (open hatch). Skin-burns occur when air temperatures rise above the horizontal line.

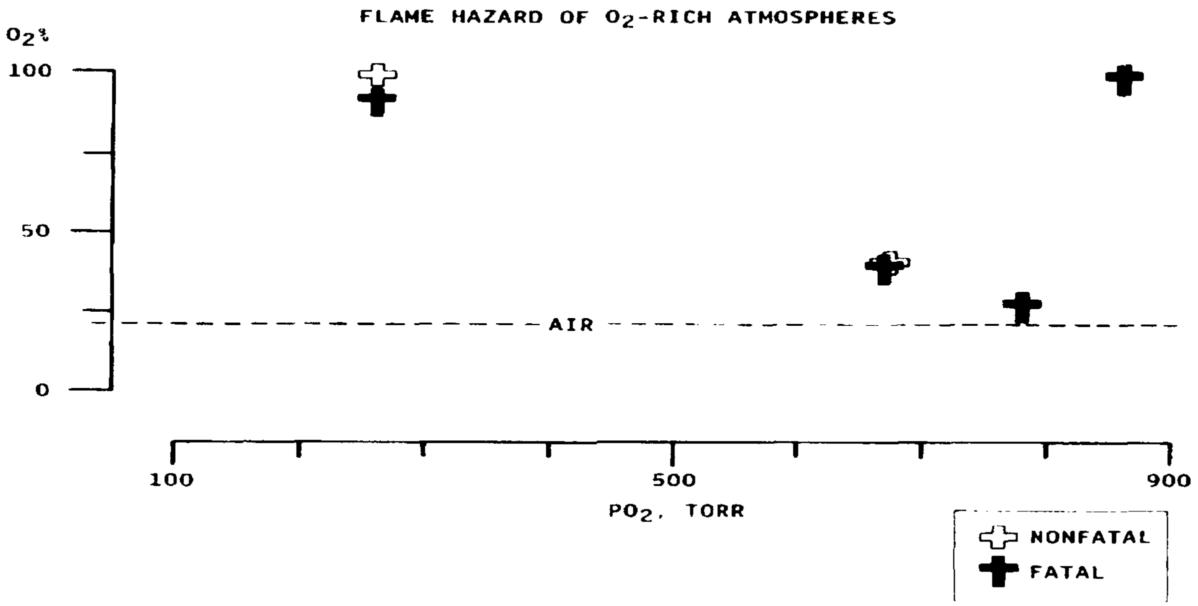

Fig. 2. FLAME HAZARD OF O_2-RICH ATMOSPHERES. Symbols define the P_{O_2} and O_2 concentrations of chamber atmospheres in chich fires caused injuries or deaths.

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

Flammability Studies

According to Cook, Meirer, & Shields (1967), the behavior of combustion processes in N_2-O_2 atmospheres varies according to the $O_2\%$ and the gas pressures. The addition of O_2 to a pressurizable chamber raises the $O_2\%$ without changing the P_{N_2}. The resultant atmosphere lowers the ignition temperature and raises the burning rate of solid materials. Chamber pressurization with a N_2-O_2 mixture of fixed composition increases the P_{O_2} without changing the $O_2\%$. This also lowers the ignition temperature and raises the burning rate of solids. Increasing the $O_2\%$ without changing the P_{O_2} serves to increase the burning rate of cloth (Cook, Meirer, & Shields, 1967).

Since the behavior of combustion processes in N_2-O_2 atmospheres varies according to the $O_2\%$ and gas pressures, the relative effects of $O_2\%$, P_{O_2}, and P_{N_2} on flammability can be analyzed by plotting isopleths of combustion activity on $O_2\% - P_{O_2}$ graphs. The $O_2\%$ (Y axis) is functionally related to P_{O_2} (X axis) by equation 1,

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

which conforms to the general equation for a straight line. The slope of the line, $100/P_B$, intersects the X axis at 0.

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

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

The P_{N_2} 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

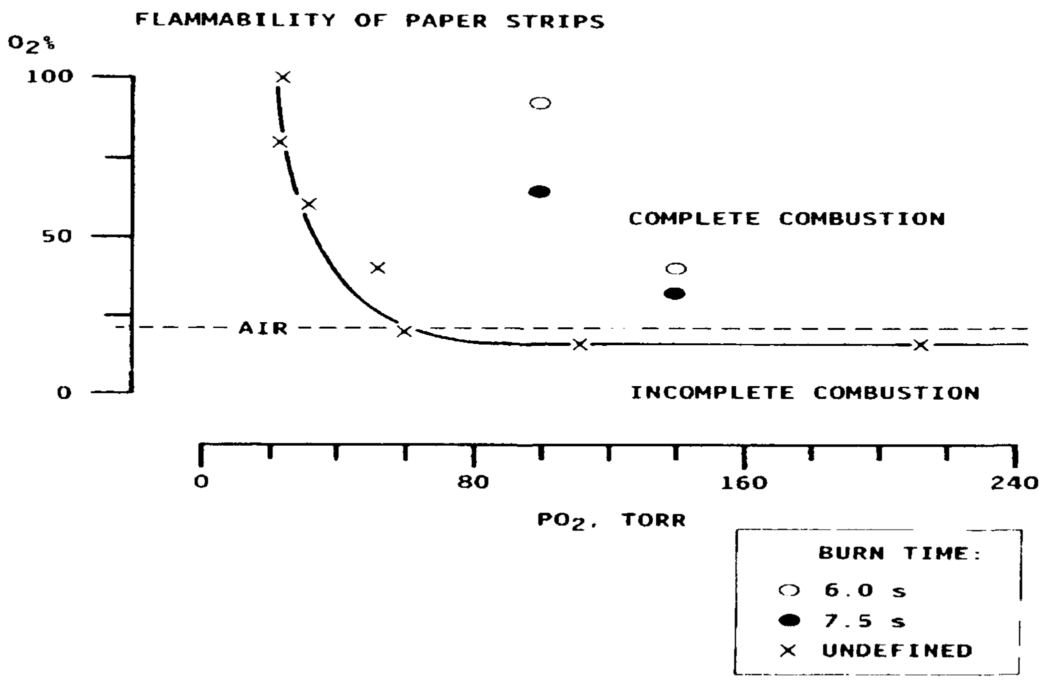

Fig. 3. FLAMMABILITY OF PAPER STRIPS. The position of the symbols defines the P_{O_2}'s and O_2 concentrations of experimental atmospheres. Each symbol represents the burn time of paper strips (see INSET). "Undefined" burn time refers to the incomplete combustion of paper strips. Atmospheres on or below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

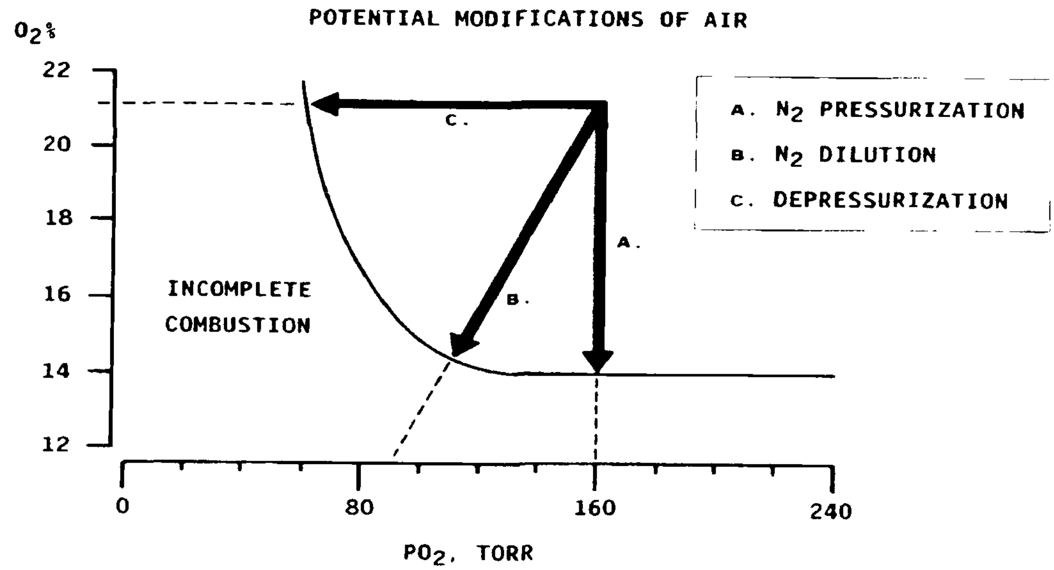

Fig. 4. POTENTIAL MODIFICATIONS OF AIR. Three solid arrows represent unique modifications (see INSET) of sea level air that produce a flame supporessant atmosphere. Atmospheric conditions on or below the curve do not support the complete combusion of paper strips.

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.

N2 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 ≤ 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

MODIFICATION PROCEDURE	PRESSURE CHANGE	GUIDELINES
N_2 DILUTION	▼ pO_2	Hypoxia
N_2 PRESSURIZATION	▲ P_B	Barotrauma
	▲ pN_2	N_2 Narcosis
	eventual ▼ P_B	Barotrauma, Decompression sickness, Hypoxia
DEPRESSURIZATION	▼ pO_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 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

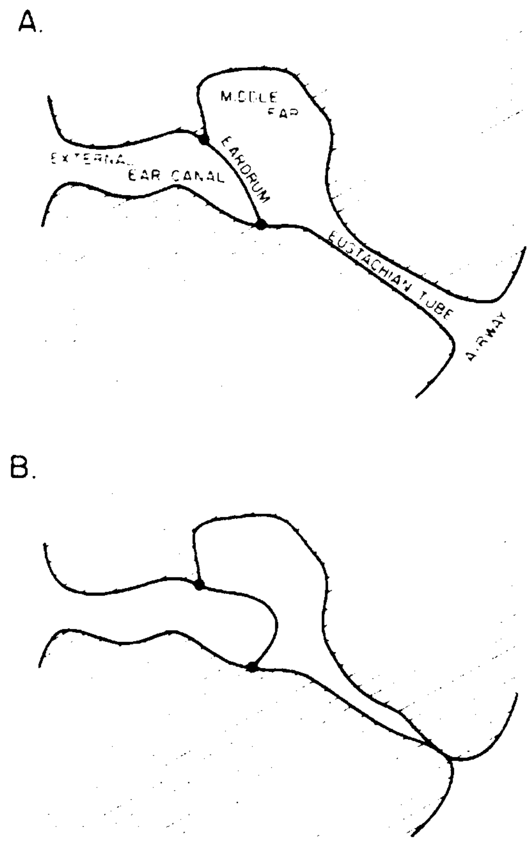

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Fig. 5. BAROTRAUMA OF THE MIDDLE EAR. Bone (cross-hatching) completely surrounds gas-filled spaces of the ear. Graph A shows the position of the eardrum when there is no pressure difference between the external and middle ear cavities. Graph B shows 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.

threshold values for DCS and N_2 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_2 in compressed air suggesting that limiting the N_2 pressurization to P_{N_2}'s <1064 torr avoids the risk of DCS upon returning to sea-level air. This P_{N_2} would cross the 160 torr coordinate of the X axis at an O_2% 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_{N_2} <1064 torr.

O_2 is absorbed by body fluids and binds to heme pigments in all cells. O_2 transport to the cells is driven by gradients of P_{O_2} that exist between the atmosphere and the cellular fluids. Oxygen may damage the lung when the P_{O_2} exceeds 380 torr (Shilling, Werts, & Schandelmeier, 1976), so it is important to emphasize that N_2 pressurization does not change the P_{O_2} in a sealed chamber. Therefore, pulmonary oxygen toxicity is not a primary medical concern of N_2 pressurization.

Flame extinction by rapid N_2 PRESSURIZATION has been successfully tested on laboratory animals (Dressler, Robinson, Gann, Stone, Willimas, et al., 1977). N_2 PRESSURIZATION to 6% O_2

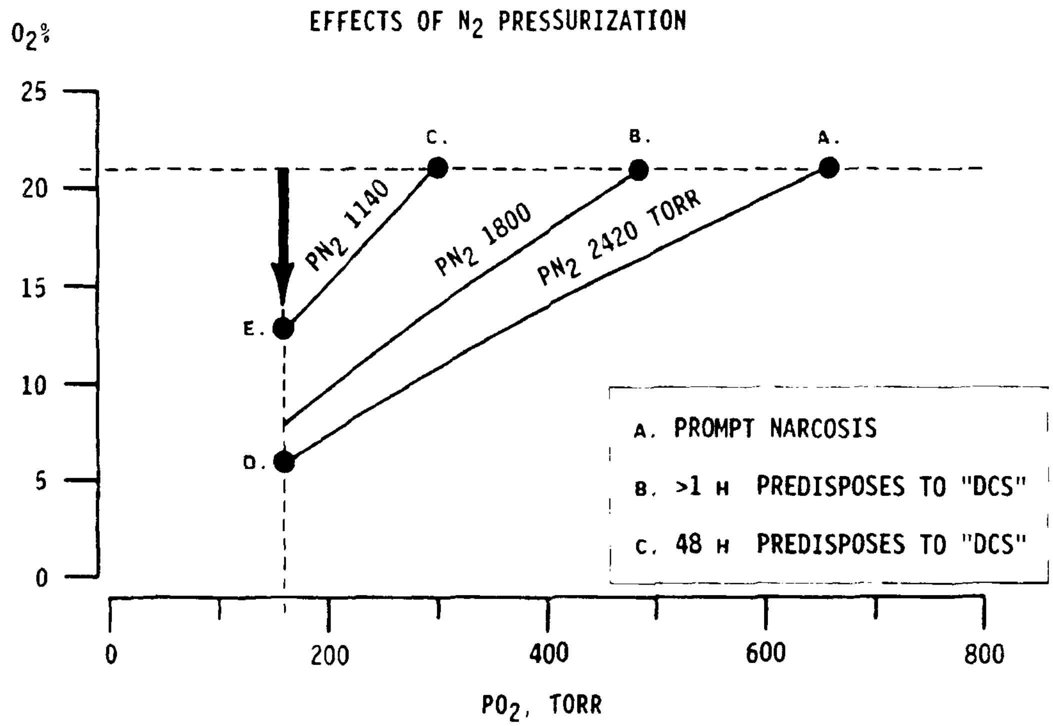

Fig. 6. EFFECTS OF N_2 PRESSURIZATION. A solid arrow represents the N_2 pressurization of sea level air. Three solid curves are N_2 isobars that produce narcosis or predispose humans to decompression sickness (see INSET) in hyperbaric atmospheres. Specific points on the graph are discussed in the text.

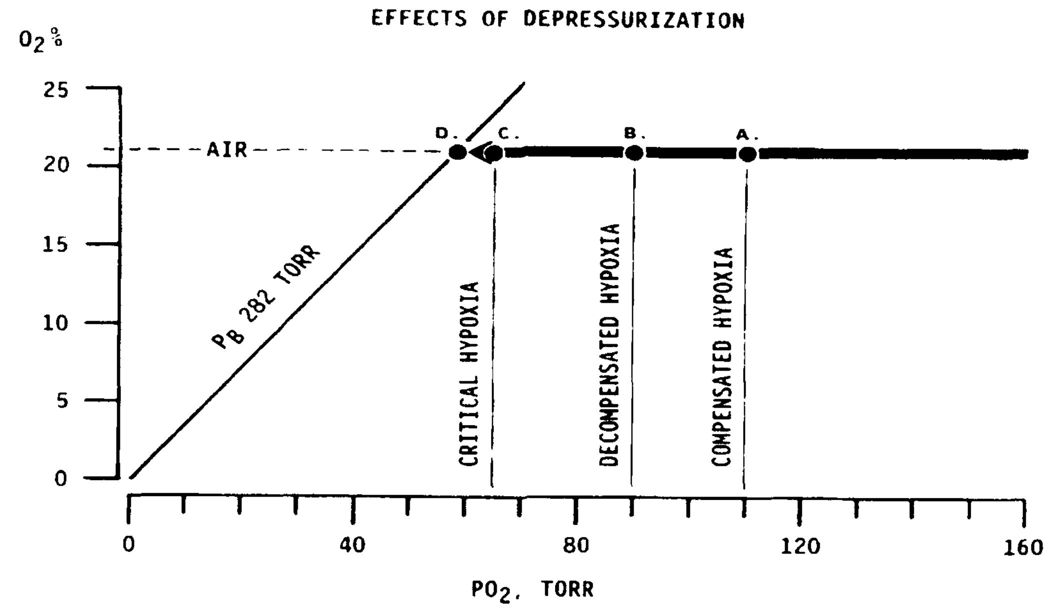

Fig. 7. EFFECTS OF DEPRESSURIZATION. A solid arrow represents the depressurization of sea level air to an isobar of hypobaric pressure. Three vertical isobars of O_2 represent thresholds to progressively severe hypoxia in unacclimatized humans.

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 lease one of the following medical disorders; mediastinal emphysema, 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 P_{O_2}. Points A-C of Figure 7 represent the threshold P_{O_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 P_{O_2}

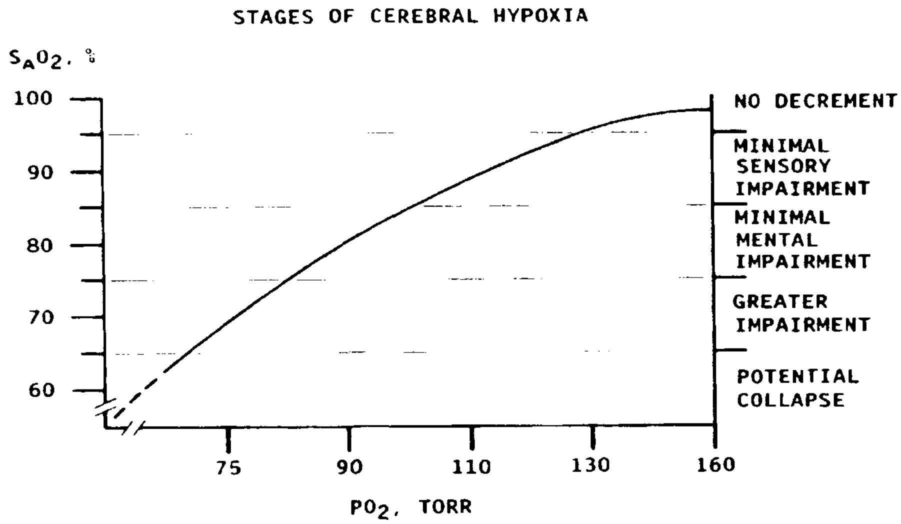

Fig. 8. STAGES OF CEREBRAL HYPOXIA. A visual best-fit curve is drawn through the scatterplot of data published by McFarland (1970). Percentage saturation of arterial

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_2 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_{O_2} 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_{O_2} 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_{O_2}'s known to impair the health of exposed populations (Randel, 1971).

There are conflicting opinions about the minimum P_{O_2} 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_{O_2} = 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_2%. His findings, and those of other investigators, are summarized in a plot of the S_aO_2 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_{O_2}. The curve is intersected by a zone of minimal sensory impairment at P_{O_2}'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_{O_2}'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_{O_2}'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_{O_2}'s of 100-85 torr and greater impairment at P_{O_2}'s of 85-70 torr. Exposure to P_{O_2} $<$70 torr may cause the individual to collapse (McFarland, 1970). Based on Figure 8, it is reasonable to postulate that the minimum P_{O_2} for unacclimatized humans is 130 torr, below which the risk for hypoxic impairment of health or performance increases with the reduction of ambient P_{O_2}.

Figure 8 does not identify the domains of P_{O_2} 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[1]. It is therefore important to consider effects other than cerebral hypoxia when attempting to define the *minimum* P_{O_2} for safe occupation of chambers.

Depressurization of the atmosphere may cause barotrauma and DCS, both of which were discussed as potential complications of N_2 PRESSURIZATION. DCS is known to occur when air is depressurized to P_B = 282 torr (point D, Figure 7) and may occur at even less severe decreases of P_B (U.S. Naval Flight Surgeon's Manual).

<u>N_2 Dilution Hazard.</u>

With this approach, there is no change of P_B that could cause barotrauma, nor does the slight increase of P_{N_2} produce narcosis. The effects of hypoxia from N_2 DILUTION are presumably equivalent to the effects of hypoxia from DEPRESSURIZATION

[1] There are literally hundreds of inorganic and organic vapors that contaminate submarine atmospheres. The prevalent contaminant, CO2, exists at molar concentrations of approximately 1%.

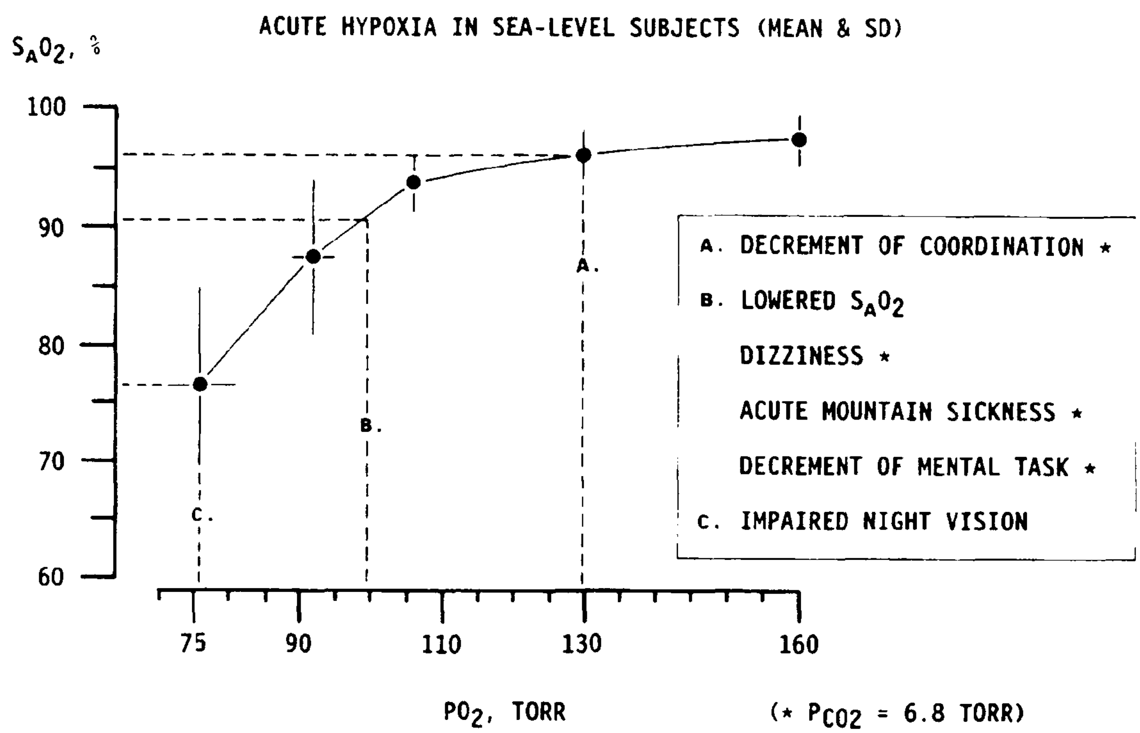

Fig. 9. ACUTE HYPOXIA IN SEA-LEVEL SUBJECTS. A visual best-fit curve is drawn through the mean values of experimental P_{O_2}'s studied by the author and colleagues. The INSET describes significant medical and physiological conditions encountered at the specific isobars of O_2. Axes were defined in the legend for figure 8.

when both atmospheres contain equivalent reductions of the P_{O_2}.

STUDIES OF HYPOXIA AT NORMOBARIC PRESSURE

Six experiments were performed by military scientists (see ACKNOWLEDGEMENTS) in which separate groups of volunteers [2] breathed 10%, 12%, 13%, or 17% O_2 without knowing the composition of the gas. The objective was to determine a minimum atmospheric P_{O_2} that permits safe occupancy of chambers for periods of days. All subjects were trained to perform one or more tasks of mental function before the experiment began and all completed a control experiment in 21% O_2. Measurements were made of the S_aO_2, 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 Insitute 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 P_{O_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[1]. 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 P_{O_2} to 130 torr. Therefore, N_2 dilution may be used to reduce the O_2 concentration to 17%. Further reduction of the P_{O_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_2 concentrations produced by N_2 dilution. Physiological adaptation to hypoxia will abolish the discomfort of multiday exposures to 13% O_2(P_{O_2} 99 torr), as reported by Shukitt, Burse, Banderet, et al., (1989). Gradual use of N_2 DILUTION to reduce the O_2 concentration below 17% may avoid the discomfort of abrupt, multiday exposures to 13% O_2. A second adjunct is the addition of a respiratory stimulant, CO_2, to the atmosphere. CO_2 is known to enhance O_2 delivery to the tissues by stimulating ventilation, improving the release of O_2 from hemoglobin, and dilating blood vessels. Preliminary studies indicate that 13% O_2 - 3% CO_2 - balance N_2 does not degrade mental performance in resting subjects (Knight, Luria, Socks, et al., 1987). A third adjunct is the use of N_2 PRESSURIZATION to supplement N_2 DILUTION, as discussed in the following concluding paragraphs .

TABLE 2		
P_{O_2} torr	Safe max P_B (torr)	$\%O_2$
120	880	13.6
130	890	14.6
140	900	15.5

Huggett suggested that an atmosphere of 128 torr O_2-balance 722 torr N_2 reduces the flame hazard of combustible materials by raising the heat capacity of the atmosphere. His reason for raising the P_{N_2} to 722 torr was based on flame suppression (Huggett, 1969). The subsequently proposed use of 130 torr O_2-balance 870 torr N_2 (Knight, 1985) took into account the hazard of DCS in flame-suppressant atmospheres. More modest N_2 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_{N_2} of 760 torr (the tissue P_{N_2} 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_{N_2} to ambient $P_B \leq 1$ (Behnke, 1967). In a binary gas mixture of N_2 and O_2, a range of safe maximum P_B's can be computed as a function of the atmospheric P_{O_2}. A sample range is shown in Table 2.

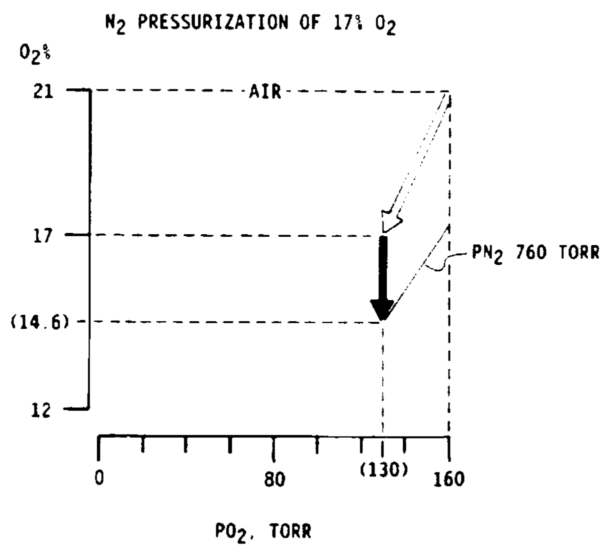

Fig. 10. N_2 PRESSURIZATION OF 17% O_2. Sea level air is initially modified by N_2 dilution (open aarrow) and further processed by N_2 pressurization (solid arrow). The solid curve is a N_2 isobar for 760 torr. Intercepts of the dashed lines are discussed in the test for Table 2.

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_2 DILUTION to lower the $O_2\%$ to 17, where the P_{O_2} is 130 torr. Additional N_2 PRESSURIZATION is used for two reasons; (a) the $O_2\%$ is lowered to 14.6 without changing the P_{O_2} and (b), the atmosphere can be decompressed to P_B - 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_2 at P_{O_2} = 130 torr for 4 h without hypoxemia or decrement of psychomotor performance (Knight, Luria, Socks, et al., 1987).

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DISCLAIMER

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_2	molecular oxygen.
$O_2\%$	The molar concentration of oxygen, expressed as a percentage of the gas mixture.
N_2	molecular nitrogen.
P_{AOG}	The combined partial pressures of gases other than oxygen and nitrogen in the atmosphere, expressed in units of torr.
P_B	The barometric pressure, expressed in units of torr.
P_{N_2}	The partial pressure of nitrogen, expressed in units of torr.
P_{O_2}	The partial pressure of oxygen, expressed in units of torr.
s	seconds.
S_aO_2	The O_2 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_2 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_2 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_2 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_aO_2): The amount of oxygen combined with hemoglobin, expressed as a percentage of the O_2 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 $P_{O_2} \geq$ torr. The degree of injury can progress to an irreversible stage depending on the level of P_{O_2} and duration of exposure (Shilling, Werts, & Schandelmeier, 1976).

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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_2 PRESSURIZATION - the addition of compressed N_2 to air. 3. DEPRESSURIZATION - the partial evacuation of air from the chamber. 4. N_2 DILUTION - the exchange of N_2 for O_2. The primary medical hazards of flame-suppressant atmospheres are barotrauma, N_2 narcosis, decompression sickness, hypoxia and inhalation toxicity. Experimental evidence supports the use of N_2 DILUTION to suppress flames aboard patrolling submarines. One or more of the following adjuncts may enhance the use of N_2 DILUTION without impairing human health: Physiological adaptation to hypoxia, addition of CO_2 to the atmosphere and N_2 PRESSURIZATION.

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