Oxygen: Health Effects and Regulatory Limits

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Introduction

Probably the biggest source of confusion and controversy involving confined spaces is the acceptable limit for atmospheres deficient or enriched in oxygen. This confusion and controversy has arisen, in part, because oxygen is essential for life, and because people can adapt in both the short-term and the long-term to oxygen levels both greater than and less than they are at sea level. Sea level, of course, is merely a convenient altitude of reference. There is no particular significance to this altitude, as people live and work quite comfortably at attitudes far below and far above this height.

Oxygen Deficiency

Complicating things further is the fact that the condition present at the legal limit for workplace exposure (19.5%) can be encountered at an altitude of 610 m (2000 feet). This altitude is readily accessible by car from sea level in many areas. One, in fact, can drive to this altitude and go considerably higher and experience no noticeable symptoms, and then be left to wonder what is the purpose for this choice and what is the concern that it reflects.

Oxygen levels are measurable in units of concentration and partial pressure. Oxygen concentration remains constant within normal habitable altitudes. This results from the relative constancy of composition of the atmosphere (Moran & Morgan 1989). Total atmospheric pressure, and by implication, the pressure of oxygen, vary according to altitude and barometric pressure. The pressure of the normal atmosphere at sea level is 760 mm Hg (millimetres of mercury). The concentration of oxygen in the normal atmosphere is 20.9% of the total of the gases (mainly nitrogen and oxygen). The pressure, but not the concentration of oxygen, decreases with altitude.

Oxygen deficiency is a major concern in the occupational setting and the subject of several standards and many regulations. Typically, the following Table 1 or a similar version which, appears in publications, summarizes the effects of acute exposure to oxygen-deficient atmospheres as commonly reported based on concentration and partial pressure (after NIOSH 1976a, Miller and Mazur 1984, after ANSI 1992, after CSA 1993). (For explanation of the acronyms, please refer to the glossary at the end of the document.)

The origins and wording of this table are not readily apparent. The table does not appear historically in the ANSI standards on confined spaces (ANSI 1977, ANSI 1989, ANSI 1995, ANSI/ASSE 2003), nor NFPA 306 which is concerned with gas hazards on ships (NFPA 1988, NFPA 1993). NFPA 306 dates back to 1922.

Table 1
Effects of Acute Exposure to Oxygen Deficient Atmospheres

	Atmospheric Oxygen (dry air, sea level)	
Effect	**Concentration** %	**Pressure** mm Hg
no symptoms	16 to 20.9	122 to 159
increased heart and breathing rate, some loss of coordination, increased breathing volume, impaired attention and thinking	16	122
abnormal fatigue upon exertion, emotional upset, faulty coordination, impaired judgment	14	106
very poor judgment and coordination, impaired respiration that may cause permanent heart damage, nausea and vomiting	12	91
nausea, vomiting, lethargic movements, perhaps unconsciousness, inability to perform vigorous movement or loss of all movement, unconsciousness followed by death	< 10	< 76
convulsions, shortness of breath, cardiac standstill, spasmatic breathing, death in minutes	< 6	< 46
unconsciousness after one or two breaths	< 4	< 30

This information is also absent from historical publications by NIOSH on confined spaces (NIOSH 1979). Articles on confined spaces, such as, Anonymous, 1967, and Allison 1976a and Allison 1976b, do provide some discussion about oxygen deficiency. The latter article by Allison (1976b) indicated that 19.5% for oxygen was the 'accepted percentage to support life'. Miller and Mazur (1984) reference Beard (1982) and Cooper (1981) as sources of their information.

The information contained in Table 1 does appear in historic standards on respiratory protection (ANSI 1980) and guides (NIOSH 1976). (Note,.that ANSI standards on respiratory protection preceded the existence of NIOSH.)

The ultimate origins of the information appear to reflect experiments performed in aerospace medicine and later adopted as the basis for discussion by the ANSI Z88.2 committee on respiratory protection. References, such as NASA (1964) and NASA (1973), contain information possibly used in later references, such as Davis (1979), and also provide historical references.

The situation highlighted in Table 1, along with comments reflected in the article by Allison (1976), hint at the complexity of the questions raised. The outcome of situation apparently reflects the divergence of vision of two groups on how to manage the reality within which people work within the environmental reality in which people live. These environments present contradictions and complexities that deserve acknowledgement and recognition in order to manage the combined reality in a beneficial and unambiguous manner. In order to do this, the following background information is essential.

• Confined Space Accidents and Atmospheric Hazards
Of considerable interest to the industrial hygienist is the composition of contaminated atmospheres associated with accidents that occur in confined spaces (McManus 1999). This information provides the key to better understanding about the hazardous nature of these workplace environments. Ultimately, this information would determine the nature and scope of the response needed to address and manage these conditions. OSHA and NIOSH reports on fatal accidents occurring in confined spaces provided the main

source of information about this subject in recent times (OSHA 1985, NIOSH 1994). Both reports provided descriptive summaries of individual accidents. These made possible further speculation about the composition of the atmosphere present at the time of the accident. Sometimes the summary alluded to the presence of more than one hazardous substance. Unfortunately, these summaries provided little or no measurement data about the composition of the hazardous atmosphere involved in the accidents.

Anecdotal information in the accident summaries provided some indication that these atmospheres are more complex than originally described. As well, there are discrepancies between the progression of events that actually occurred versus what could be expected based on controlled studies of the toxic agents implicated in the accidents. That is, the outcomes produced by some of these substances under controlled conditions differed from what was observed during accidents attributed to them.

Considerable similarity exists in the progression of events in individual accidents involving hazardous atmospheric conditions. During a typical accident, the victim usually is affected by the atmospheric condition either at the time of entry or soon afterward. This individual collapses and may yell for help, or is discovered soon afterward by someone outside the space. The discoverer or some other individual nearby undertakes the role of would-be rescuer and enters the space without ventilation or respiratory protection. The would-be rescuer possibly succeeds in transferring the victim from the interior of the space to the access opening after expending considerable physical effort. The atmospheric condition in the space overcomes the would-be rescuer, who then collapses. The would-be rescuer often collapses more rapidly than the victim. Additional would-be rescuers may suffer the same fate as the first. These events all occur prior to response by individuals equipped appropriately for the rescue. Either the victim, a would-be rescuer or both are fatally injured during this process.

During a real-world accident, entrants often collapse either immediately or shortly after initial contact with the hazardous atmosphere. This action suggests the presence of a rapidly acting, acutely hazardous condition. The rapid onset of debilitation under real-world conditions contrasts with the slower action of many substances, including carbon monoxide and organic solvents.

The onset of unconsciousness following exposure to carbon monoxide occurs when carboxyhemoglobin saturation exceeds 50% to 60% (NIOSH 1972). Saturation to the 50% level by an atmosphere containing 1000 ppm requires approximately 180 minutes (Stewart & Peterson 1970). This time sequence is much too slow to account for the rapid onset of unconsciousness observed during actual accident situations. This discrepancy suggests that carbon monoxide alone was not the causative agent in these accidents.

Hydrogen sulphide can cause rapid collapse when inspired in high concentration. Yet, in many accidents in which hydrogen sulphide was implicated, and in which air sampling subsequently occurred, the concentration typically was in the range of 50 ppm (OSHA 1985, NIOSH 1994). Concentrations in this range are sufficiently high to cause only eye irritation, not rapid collapse (NIOSH 1977). However, the test results possibly were not reliable or loss of the source could have occurred following the accident.

In high concentration, solvent vapours can cause rapid collapse. This response is consistent with situations in which exposure to high concentrations of solvent vapours did occur. However, solvents were implicated in only a small proportion of the fatal accidents described by OSHA and NIOSH.

Oxygen deficiency can cause rapid collapse. Collapse occurs after one or two breaths of atmospheres containing less than 4% oxygen (Miller and Mazur 1984). The rate of onset of symptoms depends on many factors including breathing rate, work rate, temperature, emotional stress, age and individual susceptibility (Timar 1983). These factors can exacerbate the effects of an oxygen-deficient atmosphere and influence the onset, course and outcome of accidents that occur under these conditions.

Loss of consciousness is a key outcome in an oxygen deficient atmosphere. At a concentration of 5% oxygen at sea level, unconsciousness in inactive subjects begins after about 12 seconds, or about 2 breaths of air (Davis 1979, Miller and Mazur 1984). For a slight increase in concentration to 6.5% oxygen, the duration of consciousness for inactive subjects increases rapidly to about 30 seconds. For active or active and highly stressed subjects, loss of consciousness would occur at higher concentrations. High

activity and high stress is the likely state of a would-be rescuer during an accident situation.

Atmospheres deficient in oxygen contain other gases that maintain total pressure at ambient levels. Carbon dioxide stimulates breathing at concentrations above normal levels and up to 70,000 ppm (7%) (NIOSH 1976b). The latter corresponds approximately with the legal level for oxygen deficiency (19.5%) adopted in many jurisdictions. Thus, elevated levels of carbon dioxide could stimulate inhalation of other contaminants present in the same contaminated atmosphere. At the same time under this circumstance, this atmosphere also could produce impairment because of the oxygen deficiency.

While atmospheres encountered in confined spaces likely are complex mixtures of contaminants, the preceding discussion strongly suggests that oxygen deficiency was responsible for the vast majority of accidents that involved atmospheric hazards (McManus, 1999).

• Gas Exchange

The exchange of gases between alveolar air and blood in pulmonary capillaries is the essential normal function of the lung. (The alveoli are the air sacs at the end of the respiratory tree.) The amount of exchange depends on the alveolar ventilation rate and the flow of blood through pulmonary capillaries (perfusion of the lungs), diffusivity through cellular membranes and solubility in blood. The driving forces are the differences in partial pressures, not concentration, in various environments involved in the process (Comroe et al. 1962).

Henry's Law describes the relationship at equilibrium between gas or vapour and liquids with which they are in contact (Reid et al. 1987). The quantity of a gas dissolved in a liquid at equilibrium is proportional to the partial pressure of the gas above the liquid. For each gas there is an individual Henry's constant. The value of the constant depends on a number of factors including temperature, pH and interactions between molecules of the gas and the solvent.

Two possible non-equilibrium situations also must receive consideration. The first involves contact between a solvent containing no gas or a weak solution and gas-rich atmosphere. Gas will dissolve into the solvent or weak solution until equilibrium is attained or other factor intervenes. The converse situation involves contact between a solution containing dissolved gas and an atmosphere containing no gas or a concentration less than the equilibrium value. Gas will effuse from the solution into the gas-lean atmosphere until equilibrium again is attained or other factor intervenes. Both of these processes occur in the lung and the tissues as part of gas exchange.

The relationship between atmospheric and other gases and body fluids, such as blood and extra- and intra-cellular fluids is a critical part of the process of transport and respiration. These considerations represent a direct application of Henry's Law. Oxygen diffuses into the liquid part of the blood in the lung and is transported to regions having lower concentration. This process occurs because the partial pressure of atmospheric oxygen exceeds the equilibrium partial pressure of dissolved oxygen in the fluid of the blood. Carbon dioxide diffuses into the liquid part of the blood from the tissues and effuses into airspaces in the lung. The latter process occurs because the partial pressure of dissolved gas exceeds the equilibrium partial pressure of atmospheric gas.

Gases and vapours that do not react with components of tissue or cellular fluids pass freely across the membrane barrier in both directions. Gases and vapours diffuse in response to the pressure gradient from an area of high partial pressure to an area of low partial pressure. The difference in partial pressure between alveolar air and the blood determines the net direction of flow. Gases and vapours will diffuse across the membrane barrier into or from a particular volume of blood until equilibration occurs (partial pressures become equal), or the flow has reached the end of the alveolar-capillary contact (Comroe et al. 1962, Bouhuys 1974).

Under normal conditions the partial pressure of oxygen in alveolar air is greater than that in blood entering the pulmonary capillaries. At the same time, the partial pressure of oxygen in tissue capillaries is greater than that in tissue fluids and greater in tissue fluids than in cells of the body. Conversely, the partial pressure of carbon dioxide is higher in the cells than in the intercellular fluids, higher in the intercellular

fluids than blood flowing through tissue capillaries and higher in pulmonary capillaries than in alveolar air (Bouhuys 1974).

During the breathing cycle the alveolar partial pressure of oxygen increases from a minimum of 97.9 mm Hg to a maximum of 101.5 mm Hg. The corresponding alveolar partial pressure of carbon dioxide changes from 40.8 mm Hg to 38.2 mm Hg. However, these changes in partial pressure do not correspond exactly to the inspiratory and expiratory motions of the chest. The change in alveolar partial pressure is not the same for the two gases. Metabolism consumes more oxygen than the amount of carbon dioxide produced. This means that a greater amount of oxygen is exchanged per unit time than carbon dioxide. The relative amount of carbon dioxide produced and oxygen taken up depends on metabolic activity, i.e., work (Comroe et al. 1962).

Oxygen tension of mixed venous blood entering the pulmonary capillaries is 40 mm Hg. Oxygen tension of oxygenated blood in the pulmonary veins is 100 mm Hg. This is identical to the partial pressure of oxygen in the alveolar space. The normal time spent in the pulmonary capillary bed is 0.75 s. The oxygen tension increases to almost 100 mm Hg in 0.35 s or less. This is less than half of the normal transit time. This efficiency provides redundancy for situations that are less than ideal (Comroe et al. 1962). In normal individuals only during the most strenuous of exercise when blood flow through the capillaries is extremely rapid is there insufficient time for complete equilibration. This may not be the case in individuals whose lung and circulatory function is compromised by disease, age, obesity or lack of physical conditioning. The combination of the stress induced by the situation, coupled with these factors, easily could provide the required conditions for insufficiency in gas exchange.

This process is affected by the diffusing capacity of the pulmonary capillaries and other factors. On a micro scale, this process is very complex. Ventilation of the alveoli occurs only during inspiration. On the other hand, blood flow and gas exchange occur continuously. Imbalance between the rate of ventilation and perfusion causes inefficient exchange between alveolar airspaces and the blood.

Diffusion through cellular membranes does not limit gas exchange. The rate of uptake or clearance of a gas or vapour depends on solubility in blood, the alveolar ventilation rate and the perfusion rate. The factor limiting the importance of the alveolar ventilation rate compared to the perfusion rate is solubility of the gas or vapour in the blood (Farhi 1967). Clearance of a relatively insoluble gas or vapour depends almost exclusively on the perfusion rate. The alveolar ventilation rate has little effect. For example, the rate of clearance from the blood of xenon, a relatively insoluble gas, depends mostly on the perfusion rate. Oxygen also behaves as a relatively insoluble gas. The rate of uptake of oxygen is perfusion-limited (Bouhuys 1974).

The rate of clearance of a relatively soluble gas or vapour depends almost exclusively on the alveolar ventilation rate. The perfusion rate has little effect. Clearance of the relatively soluble vapour, diethyl ether, increases dramatically with increasing alveolar ventilation at constant perfusion rate. The rate of clearance is little affected by the perfusion rate at constant alveolar ventilation rate (Farhi 1967). The rate at which carbon dioxide leaves the blood is largely determined by the rate of alveolar ventilation. Carbon dioxide behaves as a soluble gas.

The ratio of partition coefficients of oxygen and carbon dioxide is about 1:10. Carbon dioxide diffuses 20 times more readily than oxygen through the pulmonary membranes (Bouhuys 1974).

Blood leaving the alveoli contains nitrogen in direct proportion to the alveolar partial pressure of nitrogen. No net exchange between gas and blood normally occurs because nitrogen from atmospheric air saturates the tissues of the body (Moran Campbell et al. 1984).

The critical agent that sets apart oxygen from almost other gases that exchange between alveolar spaces and the capillaries is haemoglobin. Haemoglobin reacts in the lung capillaries to form oxyhaemoglobin and releases the oxygen in the tissues. Reaction between oxygen and haemoglobin is quantified through the haemoglobin saturation curve. The haemoglobin saturation curve is an important component in understanding oxygen deficiency.

• High Altitude

People live and work through a range of altitudes. Sea level is an arbitrary elevation in consideration of overall living conditions.

Travel by large numbers of unacclimatized individuals to high altitudes has increased considerably over the last three decades. (Hultgren 1992) The transient population at ski resorts in the U.S. is estimated at one million. Most of these individuals reside near sea level. This phenomenon adds another dimension to the study of hypoxia (oxygen deficiency). Travel characteristically entails rapid ascent, often within several hours, a brief stay at altitude and rapid descent. Travel activities can include skiing, backpacking, trekking and hiking. All of these involve strenuous exercise.

Table 2 summarizes characteristics of the atmosphere at different altitudes encountered during travel (Hultgren 1992).

Table 2
Altitudes Encountered During Travel

Altitude		**Atmospheric Pressure**		**Equivalent Oxygen Level** %	**Comments**
ft	m	**Total** mm Hg	**Oxygen** mm Hg		
0	0	760	159	20.9	sea level, dry reference atmosphere
5000 to 8000	1525 to 2440	636 to 570	133 to 120	17.5 to 15.8	moderate altitude
8000 to 14,000	2440 to 4270	570 to 456	120 to 95	15.8 to 12.5	high altitude
14,000 to 18,000	4270 to 5490	456 to 390	95 to 82	12.5 to 10	very high altitude
18,000 to 29,028	5490 to 8850	390 to 249	82 to 52	10.8 to 6.8	extreme altitude

Moderate altitude includes many commonly visited and well-inhabited regions of the world. Mild discomfort may occur in susceptible individuals.

The atmosphere of habitable areas above sea level contains the same relative concentration of gases. The total pressure, and hence the partial pressures of individual components, including oxygen, decreases with increasing altitude (de Treville 1988, Lahiri et al. 1972, Davis 1979). Acclimatization from sea level to high level can require weeks or even months. This discussion will consider acute effects of transition to high altitude, as these are more likely to be comparable to events that occur in confined spaces.

The zone of high altitude begins at 8000 ft (2440 m). The latter is generally regarded as the threshold above which altitude-related illness occurs. At this altitude, the arterial partial pressure of oxygen is 60 mm Hg. Corresponding haemoglobin saturation relative to sea level is 92%. At higher altitudes, haemoglobin saturation decreases rapidly. At 14,000 ft (4270 m), arterial partial pressure is 46 mm Hg; arterial haemoglobin saturation is 82%.

The first response of a person acclimatized to sea level upon arrival at high altitude is increased ventilation at rest and during work. Ventilation increases to compensate for acute hypoxia. Hyperventilation increases

the partial pressure of O_2 and decreases the partial pressure of CO_2. The increase in alveolar partial pressure of O_2 continues during the period of acclimatization. Acclimatization requires weeks or even months to accomplish. Thus, acclimatization results in increased alveolar partial pressure of O_2 at the cost of increased ventilation and decreased alveolar partial pressure of CO_2. Decrease in alveolar and arterial partial pressure of carbon dioxide initially increases pH in blood and cerebrospinal fluid (Bouhuys 1974, Lahiri 1972, Lahiri et al. 1972, Davis 1979). The increase in pH modifies the oxygen-haemoglobin binding relationship. This results in increased haemoglobin saturation beyond what would be predicted, based solely on consideration of partial pressure. As well, haemoglobin binds oxygen more tightly at higher pH and releases less to the tissues for a given decrease in arterial partial pressure (Bellingham et al. 1970).

Despite the increase in pH, the haemoglobin dissociation curve for healthy humans shifts to the right within 24 to 36 hours after arrival at high altitudes (3 000 m or more). This shift promotes unloading of oxygen from haemoglobin, thus increasing its availability to body tissues. This increase reverts to normal upon return to sea level. Associated with this effect is an increase in the level of 2,3-diphosphoglycerate (2,3-DPG) in red blood cells. When long-term residents of high altitude travel to sea level, the reverse occurs. That is, the level of 2,3-DPG decreases and oxygen affinity of haemoglobin increases. Increased 2,3-DPG formation appears to be part of an adaptive response to high altitudes (Lenfant et al. 1968, Lenfant & Sullivan 1971).

Altitude illness and high altitude pulmonary edema are extremely rare at ski lodges below 7000 ft (2135 m), yet occur with low frequency at lodges located at 9000 ft (2745 m). Ski areas are located at higher levels. The important factor seems to be related to sleep.

High altitude pulmonary edema (HAPE) results from leakage of fluid from pulmonary capillaries (Bhattacharjya 1964). This can occur in unacclimatized persons who undertake very strenuous physical exercise at altitude, as well as the native-born, following return after prolonged stay at lower altitude. Four to eight weeks are required to de-acclimatize during which time these individuals experience a decrease in haemoglobin and red blood cells. Upon return to altitude, the hypertrophied hearts in these individuals receive insufficient oxygenation due to the decrease in haemogloblin. These changes again comment about differences between those native to low versus high altitude.

Very high altitudes are easily accessible to trekkers and climbers. Rapid ascent to these levels is accompanied by high incidence of severe medical problems, including death. The upper level, 18,000 ft (5490 m) is the limit for prolonged stay. Prolonged stay above this altitude results in deterioration, not acclimatization. This, coincidentally, also is the limit for permanent habitation.

Most people who ascend rapidly to altitudes above 10,000 feet (3050 m) experience some form of altitude effect. At this altitude, total atmospheric pressure is 530 mm Hg and the partial pressure of oxygen is 111 mm Hg. Symptoms include breathlessness, heart palpitations, headache, nausea, fatigue and impairment of mental processes (Vander et al. 1990). These symptoms are similar to those quoted for similar pressures in Table 1 describing oxygen deficiency. These effects disappear during the course of several days, although maximum physical capacity remains reduced.

Residents of high altitudes ventilate less than newly acclimatized lowlanders during exercise or in hypoxic conditions (Lahiri et al. 1972). This indicates greater efficiency of pulmonary gas exchange. Dilation of the pulmonary capillaries may account for the increase in diffusion of alveolar oxygen (Hurtado 1956). Highlanders native to 2900 m or higher tolerate hypoxia better than acclimatized lowlanders and apparently can work harder (Lahiri et al. 1972). People living at altitude are on the steep slope of the oxygen-haemoglobin dissociation curve. This means that a slight change in the oxygen tension delivers more oxygen to the tissues (Hurtado 1956).

There are many genetic variants of haemoglobin in humans. Some lead to disease, whereas others represent adaptation to environmental conditions, such as high altitude (Bouhuys 1974). Many variants have higher or lower affinity for oxygen than "normal" haemoglobin (Stamatoyannopoulos et al. 1971). In general, the higher the affinity for oxygen, the higher the capacity.

An important effect demonstrated by travel to high altitude is a progressive decrease in maximum exercise

capacity and maximum oxygen consumption and decrease in maximum heart rate (West et al. 1983). This decrement occurs even at moderate altitudes and led to increases in times of 5% to 10% for distance races in the Mexico Olympics. The altitude of Mexico City is 7350 ft (2240 m) (Grover et al. 1986).

Decreased performance capacity could have important significance in accidents that occur in confined spaces. This could be especially significant in oxygen-deficient atmospheres during rescue attempts. The rescuer operates under extreme physical and emotional duress. Decreased performance capacity considerably increases the risk of exceeding one's limits under such circumstances.

Adaptation or acclimatization from lower to higher altitudes certainly is possible and occurs all the time. The ability to climb to the top of Mount Everest by people born into low altitude environments without supplemental oxygen is the supreme testimony to that achievement. Adaptation or acclimatization differs from being native-born to the altitude. Altitude-born people and animals have greater number of capillaries in muscle. This enables performance of work at a rate not possible in newcomers even after prolonged residence at altitude (Hurtado 1956). Hence, adaptation or acclimatization is never complete in newcomers.

Davis (1979) summarized the literature on acclimatization as follows:
• people vary in their ability to acclimatize
• the limiting altitude for acclimatization for dwellers at sea level is about 5500 m (18,000 ft), subject to individual differences
• mountaineers can achieve partial acclimatization to about 7000 m (23,000 ft), subject to individual differences
• deterioration in acclimatization begins around 6100 m (20,000 ft)
• drug therapy produces limited benefit
• recommended acclimatization schedule : spend 10 days at each of 6000 to 7000 ft, 9000 to 10,000 ft, 12,000 to 13,000 ft before proceeding to the next higher altitude (Bhattacharjya 1964)

• Hypoxia (Oxygen Deficiency)
A condition that mimics the effects of hypoventilation in normal individuals is exposure to an atmosphere containing less than the normal partial pressure of oxygen. In the occupational setting, this condition is produced by asphyxiants. Asphyxiants interfere with the supply or use of oxygen in the body. Asphyxiants include both simple asphyxiants and chemical asphyxiants. Simple asphyxiants include acetylene, argon, ethylene, hydrogen, helium, neon, nitrogen, propylene and water vapour, mist or steam (ACGIH 1994).

Simple asphyxiants are physiologically inert; that is, they do not affect biochemical processes. Chemical asphyxiants interfere with cellular respiration. Simple asphyxiants dilute or displace the normal atmosphere, so that the resultant partial pressure of oxygen is insufficient to maintain oxygen tensions at levels needed for normal tissue respiration. The areas of the body considered most sensitive to oxygen deprivation are the brain and myocardium (heart muscle). Cerebral hypoxia occurs when the partial pressure of inspired oxygen is lowered to 60 to 70 mm Hg (Comroe et al. 1962). Brain cells perish in three to five minutes under conditions of complete hypoxia. Damage sustained by these oxygen-sensitive tissues is not reversible upon restoration of the atmosphere (Ayers et al. 1969, Davis 1979).

Table 3 summarizes physiological effects of brief exposure (8 to 10 min) to oxygen-deficient atmospheres on resting subjects (Comroe et al. 1962). (Minute volume is the amount of air expired per minute. Alveolar ventilation rate is the amount of air expired that equililibrates (exchanges) with alveolar gas per minute.

The characteristic response to hypoxemia (low oxygen in the blood) induced by breathing an oxygen-deficient atmosphere is an increase in depth (tidal volume) and frequency of breathing. This is a direct response to triggering of oxygen chemoreceptors in the carotid and aortic bodies by the decrease in arterial partial pressure. These receptors are somewhat insensitive and not immediate in their response. Atmospheric oxygen concentration must decrease to 16% (sea level) prior to the initiation of response. Said another way, the delay in increasing the depth and frequency of breathing in these situations appears to correlate with decrease in haemoglobin saturation to the steep part of the curve.

Table 3
Effect of Brief Exposure to Oxygen-Deficient Atmospheres

Oxygen		Breathing Frequency (breaths/min)	Minute Volume L/min	Alveolar Ventilation Rate L/min
Concentration %	**Volume** mL			
20.9	500	14	7	4.9
18	500	14	7	4.9
16	536	14	7.5	5.4
12	536	14	7.5	5.4
10	593	14	8.3	6.2
8	812	16	13	10.4
6	-	-	18	-
5.2	-	-	22	-
4.2	933	30	28	23.2

The apparent delay in response could be construed as an emergency response when hypoxemia becomes severe. This may not be the case, since there is a similar delay in the onset of more rapid and deeper breathing following the start of vigorous exercise, such as running, from resting status. Hypoxemia is capable of causing increased respiration in normal individuals. However, hypoxemia greater than that seen in most patients with chronic pulmonary disease is required before breathing in normal individuals is stimulated conspicuously (Comroe et al. 1962).

The extent of saturation of haemoglobin reflects partial pressure of oxygen in the blood. Many normally occurring situations, including changing metabolic status from rest to vigorous exercise, rapid ascent to high altitude, and cardiac or pulmonary insufficiency are characterized by reduced alveolar and therefore arterial partial pressure of oxygen.

Decrease of arterial partial pressure from 100 to 60 mm Hg causes only a 10 % decrease in haemoglobin saturation. Hyperventilation by a normal person at sea level produces little change in haemoglobin saturation for this reason (Vander et al. 1990). At arterial partial pressures less than 50 mm Hg, saturation of haemoglobin decreases rapidly. Oxygen tension in tissue capillaries is 40 mm Hg. Oxygen dissociates from the haemoglobin molecule and enters into physical solution in the plasma whenever the oxygen tension in the plasma decreases. Thus, as fast as oxygen diffuses from the plasma into tissues through the capillaries, it is replenished by oxygen dissociating from the haemoglobin (Bouhuys 1974). Oxygenated haemoglobin gives up large quantities of oxygen under these conditions.

Another aspect in exposure to reduced levels of oxygen (normal resting subjects) is transfer from alveolar spaces into blood (Table 4) (Comroe et al. 1962).

As mentioned previously, the normal time spent in the pulmonary capillary bed is 0.75 s. Under normal conditions, the oxygen tension increases to almost 100 mm Hg in 0.35 s or less. This results from the steepness of the pressure gradient across the capillary membranes. The change in pressure gradient with time as blood perfuses through the capillary is hyperbolic and reaches equilibrium asymptotically. Under normal conditions, the alveolar-capillary pressure gradient is approximately 60 mm Hg. This causes rapid transfer of oxygen from the alveolar airspace into the fluid of the capillary. The partial pressure of O_2 in blood and that in the alveolar airspaces equilibrate before the end of travel through the pulmonary capillary.

Table 4
Effect of Oxygen Partial Pressure on Alveolar Gas Exchange

		Capillary Partial Pressure		Partial Pressure Gradient		Haemoglobin Saturation	
Atmospheric Oxygen %	**Alveolar Partial Pressure** mm Hg	**Start** mm Hg	**End** mm Hg	**Start** mm Hg	**End** mm Hg	**Start** %	**End** %
20.9	101	40	100	61	1	75	97
14	57	32	51	25	4	58	84
12	44	27.5	40	16.5	6	53	75

In an oxygen-deficient atmosphere containing, for example, 14% oxygen, the initial pressure gradient may be only 25 mm Hg. Because of the shallower pressure gradient, oxygen transfer occurs at a slower rate. A measurable pressure gradient exists between oxygen in the alveolar airspace and blood at the end of the capillary. Under this condition, equilibration fails to occur. Hence, a decrease in the partial pressure of O_2 in inspired air leads to a decrease in arterial partial pressure and a decrease in saturation of haemoglobin (Comroe et al. 1962).

At low levels of oxygen, for example, 12%, oxygen tension in incoming blood decreases to 27.5 mm Hg. The pressure gradient is linear and less steep than that at higher concentrations. The rapid increase in saturation early in the passage through the capillary no longer occurs. Instead, saturation increases proportionate to distance along the capillary. As well, there is a net difference in partial pressure between alveolar air and blood at the end of the capillary due to lack of equilibration.

As the oxygen concentration or atmospheric partial pressure is reduced, haemoglobin saturation decreases. At alveolar oxygen partial pressure of 60 mm Hg, haemoglobin saturation reduces to 90%. The atmospheric partial pressure of oxygen corresponding to this alveolar partial pressure is about 120 mm Hg. At this point, most physiologists agree that symptoms of oxygen deficiency become evident (NIOSH 1976a)

Altitude introduces an additional complicating factor. The body responds to partial pressure of oxygen, rather than concentration. Total atmospheric pressure, and hence the partial pressure of oxygen, both decrease with increasing altitude. Alveolar oxygen partial pressure of 60 mm Hg corresponds to atmospheric oxygen partial pressure at 3000 m (10,000 ft). Altitudes exceeding this height are normally considered to be oxygen-deficient for individuals acclimatized to sea level (Davis 1985). At these altitudes, less oxygen depression in a workspace atmosphere is required to produce an oxygen-deficient condition. As well, a greater percentage of oxygen is required in supplied breathing air to prevent oxygen deficiency. For example, at 10,000 m (33,000 ft), an atmosphere containing 100% oxygen is needed (NIOSH 1976a).

Complicating this situation is the impact of exercise and work. Exercise decreases the time spent by blood in the pulmonary capillaries. This would further reduce saturation in an individual breathing a reduced level of oxygen. To a first approximation (this could be influenced by change in pH), the remaining pressure gradient could be estimated using reduced transit time as a fraction of normal and the linear increase of saturation with time in the capillary. For example, in 14% oxygen and 0.30 s for transit time in place of 0.75 s, partial pressure in blood would increase from 32 to 40 mm Hg. Saturation of haemoglobin would increase from 58% to 75%. Reducing the level of exercise so that the transit time increases to 0.45 s would provide only marginal increase in partial pressure in blood from 40 to 45 mm Hg. Partial pressure of 45 mm Hg corresponds to saturation of 80%. Saturation would increase during passage through the pulmonary capillaries from 58% to 80% (an increase from 75% to 80%).

A number of stressors that reflect the metabolic demand for gas exchange can modify the breathing pattern. Feedback about arterial partial pressures of oxygen and carbon dioxide and pH provides the information. Under most conditions, ventilation rate regulates arterial oxygen and carbon dioxide tensions within narrow limits. Oxygen deprivation also can become regulating. This occurs when the oxygen content of the inspired gases is reduced to nearly half that in air at sea level (approximately 11%). Hence, under normal circumstances regulation of breathing occurs by bodily requirements to control carbon dioxide tension. However, the concentration of oxygen in an oxygen-deficient atmosphere may become the regulator of breathing. Elevated levels of carbon dioxide (30,000 to 70,000 ppm) increase tidal volume, breathing rate, and minute ventilation (Bouhuys 1974).

Healthy people live long and active lives at high altitudes where arterial saturation ranges from 85% to 95%. Few patients with cardiopulmonary disease have arterial oxygen saturation less than 85%. The lower limit of arterial oxygen saturation compatible with moderately active existence depends on the abruptness with which hypoxemia develops, compensatory mechanisms and other limiting factors in the disease process. Haemoglobin saturation in persons with congenital heart disease may be less than 80% without causing disability. On the other hand, an asthmatic may sustain adequate alveolar gas exchange and arterial saturation only by extreme effort. Persons with emphysema may experience disability despite the fact that arterial saturation is 90% to 95% (Comroe 1962).

• Oxygen Enrichment (Hyperoxia)

Oxygen enrichment is the condition resulting when the partial pressure of oxygen exceeds that found under normal ambient conditions. Normal ambient conditions can include workspaces, such as deep mines, whose workings occur at depths considerably below sea level. At partial pressures considerably greater than those found in normal atmospheres, oxygen exerts both acute and chronic toxic effects.

Hyperoxia has little impact on haemoglobin saturation. Increasing alveolar partial pressure beyond normal values increases haemoglobin saturation insignificantly. This outcome results from the dynamics of the saturation process as reflected in the saturation/partial pressure curve (Bouhuys 1974).

Table 5 indicates the toxic activity of oxygen at elevated partial pressures (Yarborough 1947, Donald 1947, after Dukes-Dobos and Badger 1977, after Behnke 1978).

At partial pressures exceeding 400 mm Hg, oxygen produces respiratory irritation. In hyperbaric atmospheres exceeding 2280 mm Hg, oxygen produces nervous signs and symptoms that culminate in convulsive seizures. Oxygen toxicity is exerted in the lungs, central nervous system and the eyes, although it is probably toxic to all organs at sufficient concentration (Piantadosi 1991). Generally, the rate of onset is a hyperbolic function of the inspired partial pressure (Clark & Lambertson 1971a, Clark & Lambertson 1971b). Sensitivity of the central nervous system to the toxic effects of oxygen is considerably greater than the that of the pulmonary system. Tolerance to elevated partial pressures of pure oxygen atmospheres ranges from several minutes to two hours. Toxic action of hyperbaric oxygen atmospheres is greatly enhanced by exercise and elevated levels of carbon dioxide (Yarborough 1947). This translates into reduced tolerance time. Individual tolerance varies widely (Donald 1947).

Oxygen toxicity is expressed through production of reactive intermediates, such as the superoxide anion O_{2}^{-} and the hydroxyl radical (OH) (Freeman & Crapo 1982). The superoxide anion is highly reactive toward biological molecules. Normally, enzymic action and reaction by free radical scavengers, such as reduced glutathione, remove these species. During hyperoxia, production of reactive oxygen metabolites greatly increases and may exceed the capacity of scavengers to remove them. Tissue injury and subsequent effects in both brain and lungs appear to be related to increased metabolism (Mayevsky 1984).

Another extremely important consideration about oxygen enrichment is the increased ignitability of clothing and other combustible materials, including the skin (OSHA 1985). OSHA documented a number of fatal accidents in which oxygen enrichment occurred through inadvertent or deliberate release of pressurized oxygen gas from tanks in oxy-fuel systems. The resulting fires indicate the considerably enhanced risk of ignitability, even at normal atmospheric pressure.

Table 5
Toxic Action of Oxygen

Atmospheric Pressure		
Total mm Hg	**Oxygen** mm Hg	**Comments**
760	159	sea level
	400	respiratory irritation
	760	throat irritation; no systemic effects provided that exposure is brief
	1520	tracheal irritation, slight burning on inhalation; tolerance increased when periods of oxygen interspersed with air; reduced vital capacity develops
	>1520	signs and symptoms of oxygen poisoning: tingling of fingers and toes, visual disturbances, acoustic hallucinations, confusion, muscle twitch, nausea, vertigo, possible convulsions
	>2280	nervous signs and symptoms twitching, vertigo, anxiety, paresthesia in toes and fingers, nausea, convulsive seizures

The enhanced ignitability hazard in an oxygen-enriched atmosphere is due in part to the reduction in minimum energy needed for ignition and the greater rate of flame spread (Frankel 1991). That is, combustible materials ignite more easily and burn more rapidly in an oxygen-enriched atmosphere. Generally, ignition energy decreases with increasing oxygen concentration and rate of flame spread increases with increasing atmospheric pressure. Almost all materials will burn in pure oxygen. This situation can seriously challenge presumptions about safety in selection of materials for use in oxygen service.

Table 6 summarizes the effects of exposure of substances, fabrics and polymers to an oxygen-enriched atmosphere on ignitability (Hugget et al. 1965, Johnson and Woods 1966, after Kuchta et al. 1967, after Kuchta and Cato 1968, after Frankel 1991).

Lubricants and hydraulic fluids are the most sensitive of the types of substances for which information is available. In the case of lubricants, this sensitivity changes from oxygen-deficiency through normal concentrations through oxygen-enrichment. The lowest of the tested partial pressures corresponded to a concentration of 31% oxygen relative to the sea level dry atmosphere.

Consensus and Regulatory Standards for Oxygen
As for limits set for permissible exposure to toxic substances, those set for oxygen reflect laboratory-based studies and human experience. The standard-setting process does not involve documented judgement of expert committees in toxicology or human physiology in the same manner as other toxic agents. To illustrate, there is no TLV for oxygen. The only mention of oxygen by ACGIH in older editions of the TLV booklet was contained in the preamble (ACGIH 1994). As well, there is no documentation for oxygen in older Documentation volumes (ACGIH 1991).

Oxygen Limits Based on Concentration
Given the choice between concentration and partial pressure for setting limits for permissible exposure to oxygen, almost all respondents have opted for concentration. Sensor technology for measurement of oxygen based on partial pressure is also readily available. The latter sensors contain a large open diffusing surface, whereas the sensors used for measuring concentration contain a small opening. The larger opening of the partial pressure sensor is more sensitive because of the considerably larger surface through which diffusion can occur compared to the capillary pore sensor used for measuring oxygen concentration. The partial pressure sensor is sensitive to changes in barometric pressure, as well as altitude and weather, and requires adjustment to address these realities.

Table 6
Effect of Oxygen-Enrichment on Combustibility/Flammability

Atmospheric Pressure		
Oxygen mm Hg	**Total** mm Hg	**Comments**
159	760	normal atmosphere, sea level, dry air
range	760	decrease in autoignition temperature of hydraulic fluids with increase in partial pressure of oxygen
range	760	decrease in autoignition temperature of lubricants with increase in partial pressure of oxygen from less than normal through 760 mm Hg
236	760	increase in ignitability in oxygen/nitrogen mixture of materials (fabrics, paper, polymers) that did not burn in normal atmosphere
258	760	considerable increase in flame spread rate in combustible materials (fabrics and polymers)
319	760	decrease in ignition temperature of combustible fabrics and sheeting
760	760	slight decrease in autoignition temperature of most hydrocarbon fuels, solvents and anaesthetic gases; broadening of flammable range by increase in upper flammable limit

Almost universal in its adoption at this time is the regulatory limit of 19.5% for the lower level of oxygen permissible in confined spaces. This value applies irrespective of altitude and extent of acclimatization of the individual. The Occupational Safety and Health Administration (OSHA) of the US Department of Labor set the direction for other jurisdictions in adopting this value.

OSHA standards are unusual among regulatory standards. They provide dialogue to indicate the rationale for the decision. The dialogue also provides invaluable insight into concerns and comments raised by interveners to the process. However, the discussion is far from complete. The OSHA standards on confined spaces in general industry and shipyard employment are directed to situations that could be life-threatening following failure of the ventilation system or respiratory protection (OSHA 1993, OSHA 1994).

In the preamble to the Standard for general industry OSHA recommended 19.5% as the acceptable lower limit (OSHA 1993). OSHA stated its belief that concentrations less than 19.5% would be oxygen-deficient. Neither OSHA nor any of the interveners to the process provided any technical evidence about oxygen deficiency that could serve as the basis for informed discussion about this subject.

Interveners representing the ANSI Z88.2 Committee on respiratory protection argued that 19.5% as a lower limit was too high. They argued for a lower limit, namely 12.5%, using as the rationale, that no respiratory protection was needed at 16% oxygen. The value, 12.5%, should in their view be considered as Immediately Dangerous to Life and Health. The direction of reasoning shown by the ANSI Z88.2 Committee was considerably different from that taken by the ANSI Z117.1 Committee on confined spaces (ANSI 1989). The difference in approach taken by these Committees indicates the depth of the controversy that surrounds this issue.

In making its selection of 19.5% for the lower limit, OSHA indicated its heavy reliance on the judgement of the ANSI Z117.1 Committee on confined spaces and the NIOSH Respirator Decision Logic (ANSI 1989, NIOSH 1987). Neither of these documents provides technical justification for the value.

The OSHA Standard for shipyard employment raised the minimum acceptable level from the 16% contained

in the previous version of the rule to 19.5% (OSHA 1994). Interveners to this process included a high proportion of individuals and groups with direct, on-going experience in assessment and control of oxygen-deficient atmospheres. This group were highly supportive of the change. However, neither OSHA nor the interveners provided any technical documentation in support of this change. The Standard on shipyard employment represents a special case in confined spaces, since affected sites are located at sea level or low altitudes.

Oxygen Limits Based on Partial Pressure

The second approach to setting of limits for acceptable levels of oxygen utilizes partial pressure. Table 7 summarizes recommendations contained in various standards and guidelines (ACGIH 1994, NIOSH 1979, ANSI 1980, ANSI 1992, CSA 1982, CSA 1993). Limits provided here are contained in the source documents and not converted from concentration units.

The limit of greatest interest from the perspective of acute exposures is the IDLH (Immediately Dangerous to Life or Health). IDLH originally was defined in the NIOSH Standards Completion Project for the purpose of selecting respiratory protection (NIOSH 1990). Under NIOSH usage, the term, IDLH, is the presumed minimum concentration from which a person could escape in 30 minutes in the event of respirator failure without experiencing any escape-impairing or irreversible health effects. Since then, other groups have adopted the acronym, IDLH. Each has modified the original meaning. Under ANSI usage, IDLH means an atmosphere that poses an immediate hazard to life or produces immediate, irreversible, debilitating health effects (ANSI 1980, ANSI 1992). Under CSA, IDLH means an atmosphere where the concentration of oxygen could cause a person without respiratory protection to be fatally injured or to suffer immediate irreversible or incapacitating health effects (CSA 1982, CSA 1993).

The rationale used by ANSI and CSA in their definitions of IDLH was to select the partial pressure of oxygen that would produce 90% saturation of haemoglobin in alveolar blood (ANSI 1980, CSA 1982, CSA 1993). In the current standard on respiratory protection the ANSI Z88.2 Committee chose 83% saturation for the IDLH (ANSI 1992). These saturation values are the minimum below which symptoms of oxygen deficiency are believed to become noticeable. Neither references duration of exposure, since onset of this condition would not necessarily be immediate.

Limits based on partial pressure require use of instruments containing the partial pressure sensor, and not the capillary pore sensor. This would necessitate operator access to enable correction of readings to ensure operation in environments different from sea level.

Discussion

Selection of acceptable limits for exposure to oxygen is one of the most difficult and controversial of decisions. As indicated in previous discussion, oxygen level is influenced by barometric pressure (weather), humidity, altitude, and atmospheric composition.

Limits based on concentration are altitude independent, since concentration remains constant in normal air at the depths and altitudes normally accessible without respiratory protection. These limits, therefore, only reflect atmospheric composition caused by local contamination. However, the body responds to the partial pressure of oxygen and not to concentration. Limits based on partial pressure are altitude, barometric pressure, weather, and composition dependent. Saturation of haemoglobin depends only on partial pressure of oxygen in the local atmosphere. Therefore, altitude, barometric pressure, weather conditions, and local contamination all combine inseparably to affect performance and safety.

Previous discussion has identified the individual elements that influence atmospheric pressure, as well as the physiological basis for response to oxygen level. This discussion highlights the dichotomy between concentration- and pressure-based limits for assessing oxygen level in consensus and regulatory standards. Table 8 summarizes this information in order to provide the basis for further discussion (Anonymous 1991, Kemball 1985, McIntyre 1987, McManus 1999).

Table 7
Partial Pressure Limits for Oxygen Deficiency and Enrichment

Source	**Atmospheric Pressure Limit** mm Hg	**Equivalent Concentration** (sea level, dry air) %	**Comments**
ACGIH	$P \leq 135$	≤ 18	minimum partial pressure without need for respiratory protection; normal atmospheric pressure
NIOSH	$P \leq 122$	≤ 16	immediately dangerous to life, normal atmospheric pressure, sea level
	$P < 132$	< 17	oxygen deficiency, normal atmospheric pressure, sea level
	$122 \leq P \leq 147$	$16 \leq C \leq 19$	dangerous, but not immediately life threatening ; respiratory protection determined by qualified person; normal atmospheric pressure, sea level
	$148 \leq P \leq 163$	$19.5 \leq C \leq 21$	no modification of work procedures, normal atmospheric pressure, sea level
ANSI Z88.2-1980	$P \leq 106$	$C \leq 14$	atmospheric partial pressure of oxygen in dry air at sea level corresponding to partial pressure of 100 mm Hg in freshly inspired air in the upper portion of the lung that is saturated with water vapour at 37 °C; immediately dangerous to life or health
ANSI Z88.2-1992	$P \leq 95$	$C \leq 12.5$	dry atmosphere, sea level, immediately dangerous to life or health; may occur through any combination of reduction in oxygen content or altitude
	$95 < P \leq 122$	$12.5 < C \leq 16$	oxygen deficient - not immediately dangerous to life or health; may occur through any combination of reduction in oxygen content or altitude
CSA Z94.4-M1982	$P \leq 106$	$C \leq 14$	atmospheric partial pressure of oxygen in dry air at sea level corresponding to partial pressure of 100 mm Hg in freshly inspired air in the upper portion of the lung that is saturated with water vapour at 37 °C; immediately dangerous to life or health
CSA Z94.4-93	$P \leq 106$	$C \leq 14$	atmospheric partial pressure of oxygen in dry air at sea level corresponding to partial pressure of oxygen in inspired air in the upper respiratory passages falls to 13.3 kPa (100 mm Hg) or less; immediately dangerous to life or health

Table 8
Altitude and Weather Effects on Atmospheric Conditions

	Atmospheric Pressure sea level, dry atmosphere	**Oxygen Concentration**	**Altitude Equivalent**	
Condition	mm Hg	%	ft	m
Atmospheric				
dry atmosphere	760			
water vapour	≈ 10			
typical high pressure	(+ 28)			
record high pressure	(+ 53)			
typical low pressure	(- 32)			
record low pressure	(- 107)			
Geographic				
highest mine (Chile)	357	9.8	20 262	6 176
La Paz (Bolivia)	493	13.6	11916	3 632
Bogota (Colombia)	555	15.3	8724	2659
Mexico City	581	16	7487	2282
Denver	630	17.4	5280	1609
deep mine (Sudbury, ON Canada)	950	26.2	-6317	-1925
Dead Sea (Jordan)	799	22	-1337	-408
Qattara Depression (Egypt)	772	21.3	-440	-134
Death Valley (California, US)	768	21.2	-282	-86
Aviation				
cabin pressurization	571	15.7	8000	2440
Regulatory Limits				
16% oxygen (previous)	580		7500	2286
18% oxygen (previous)	653		4288	1307

19.5% oxygen (present)	707		2000	610
22 % oxygen (present)	798		-1394	-425
23.5 % oxygen (present)	853		-2871	-875

Humidity can vary from hour to hour and often from day to day in a location. As indicated in Table 7, 10 mm Hg would be a conservative value for the vapour pressure of water under most situations. This indicates that the contribution of water vapour to total atmospheric pressure is small. This contribution easily could become lost in fluctuations of barometric pressure. Hence, the contribution of humidity on total pressure is so small as to be ignorable under most conditions.

Based on standard total atmospheric pressure associated with the standard (dry) atmosphere and 19.5% as a regulatory limit, oxygen deficiency would occur at altitudes as low as 2000 ft (610 m), based on standard atmospheric pressure. However, atmospheric pressure varies continuously in a location from sometimes from hour to hour and often day to day.

During a period of typical high pressure at this altitude, the atmospheric pressure easily could increase from 707 mm Hg to 707 + 28 = 735 mm Hg. This would increase the oxygen concentration from 19.5% to 735/760 x 20.95% = 20.3%, relative to sea level. Under this weather condition, this location would not be oxygen-deficient according to the regulatory limit. During a period of typical low pressure at this altitude, the atmospheric pressure would decrease from 707 mm Hg to 707 - 32 = 675 mm Hg. This would decrease the oxygen concentration to 675/760 x 20.95% = 18.6%, relative to sea level. Under this weather condition, oxygen-deficiency would be more severe compared to the standard atmosphere. An unusual low would further exacerbate the oxygen-deficient condition.

It could be argued that the true altitude at which oxygen deficiency should be considered to occur would be that whose normal low pressure would be 707 mm Hg. This would correspond to a standard atmospheric pressure of 707 + 32 = 739 mm Hg and an altitude of 795 ft (242 m).

The second approach would be more protective since this would minimize the chance that oxygen deficiency could occur due simply to variation in atmospheric pressure. Adoption of this approach would permit use of an instrument that is altitude and weather independent.

The preceding is one approach to this question. Another is to incorporate all losses in partial pressure of oxygen. These would include elevation, weather pattern, and local atmospheric contamination caused by the work to be performed. This approach would require an instrument responsive to both altitude and weather conditions. Calibration could occur at sea level during an average day. Using this approach, hazard assessment could be subjected to day-to-day variability, as weather conditions and local contamination experienced change. This would be an especial concern at altitudes where partial pressures would be close to regulatory oxygen-deficient conditions and where weather conditions alone could necessitate control measures.

Instruments designed for measuring oxygen in confined spaces display in units of concentration. Some sensors function independently of altitude and variations in partial pressure of oxygen due to weather. Physiologically based oxygen deficiency may not be obvious to users of this type of equipment, because concentration would remain constant at all altitudes of normal use. The other type of sensor is sensitive to partial pressure of oxygen (and therefore, altitude and barometric pressure). Calibration of this type of instrument at sea level for use at higher altitude, or calibration at higher barometric pressure than present during actual use could cause underestimation of concentration. An ambient condition easily could be falsely identified as oxygen-deficient by an oxygen-monitoring instrument containing a sensor that is sensitive to partial pressure. On the other hand, an instrument containing this type of sensor provides the best potential

for estimating adverse conditions, since the body responds to partial pressure of oxygen, not concentration.

The question of oxygen deficiency is more complex even than discussed thus far. Demands of today's industrialized society also must be considered. Individuals acclimatize to the conditions of a particular altitude. Acclimatization brings about physiological change that occurs over a period of time. However, many people routinely work at altitudes considerably different from that to which they are acclimatized. Travel to a worksite could entail a flight in a commercial airplane whose cabin is pressurized to 8000 ft (2438 m). This corresponds to 570 mm Hg total pressure or 15.7% oxygen, relative to sea level, dry atmosphere (Bancroft 1971). For a person travelling during work time, or for the flight crew, this level technically represents an occupational exposure to an oxygen-deficient atmosphere. For long flights, this exposure can occur for most of the work day. For individuals acclimatized to sea level, travel to a location at a higher altitude coupled with work in an office tower or stay in a high-rise hotel could constitute exposure to an oxygen-deficient atmosphere. The mere act of moving from ground level to a worksite in a high-rise building in a geographic location at a higher altitude could lead to exposure to an oxygen-deficient condition.

The problem of limits for oxygen deficiency was mentioned in the original NIOSH Guide to Respiratory Protection (NIOSH 1976a). This document indicated that oxygen deficiency could develop through decrease in oxygen content or through increase in altitude. Altitudes greater than 10,000 ft (3050 m) at the time of writing of the NIOSH report were considered to be oxygen deficient. However, as mentioned in the NIOSH report, workers at altitudes of 10,000 ft (3050 m) routinely used air-purifying respirators without apparent difficulty.

As the NIOSH report optimistically commented, this problem was under study, and eventually "oxygen-deficient atmosphere" will be redefined to eliminate the present discrepancies and account for the effect of altitude. The irony in this statement is only partly apparent. The NIOSH report listed the standards of the day for oxygen deficiency. By comparison, the permissible limit for oxygen deficiency has increased, that is, has become more stringent, thus making resolution of the discrepancy even more difficult to achieve.

The former version of the ANSI Standard on respiratory protection, ANSI Z88.2-1980, only obliquely approached the question of altitude (ANSI 1980). This occurred in example problems provided for clarification in use of the equation used for calculating oxygen partial pressure. The corresponding CSA Standard, CSA Z94.4-M1982, utilized the same criteria as the ANSI Standard, but introduced an altitude limit of 3.66 km (12,000 ft) for oxygen deficiency (CSA 1982). Standard atmospheric pressure at this altitude would be 491 mm Hg. Corresponding concentration of oxygen would be 13.5% relative to sea level.

CSA Z94.4-93 did not vary from the previous version in this respect (CSA 1993). By contrast, the ANSI standard on respiratory protection, Z88.2-1992 addressed this question head-on (ANSI 1992).

The direction taken by ANSI Committee Z88.2 was not shared by ANSI Committee Z117.1 on confined spaces or by regulatory agencies such as OSHA (ANSI 1989, OSHA 1993, OSHA 1994). The approach taken by ANSI Z117.1 and OSHA on this question provided no recognition about the altitude question nor a means to resolve it.

The ANSI Standard on respiratory protection embraced the concept of partial pressure rather than concentration for resolving the question of oxygen deficiency (ANSI 1992). By taking this approach, the ANSI Z88.2 Committee created a basis for technical dialogue about this question. ANSI Z88.2 established 95 mm Hg as the partial pressure of oxygen in air for the IDLH. This could be reached at an altitude of 14,000 ft (4267 m), in an atmosphere containing 12.5% oxygen at sea level, or in some combination of altitude and oxygen deficiency.

The Standard also provides additional important information. At and above 10,000 ft, an ordinary supplied-air respirator or SCBA provides oxygen at a partial pressure less than 121 mm Hg, even though the concentration is 20.9 %. This would be equivalent to a gas mixture that provides 16% oxygen at sea level. In cases where a supplied-air respirator or SCBA would be required at these altitudes, the gas mixture must contain at least

23% oxygen at 10,000 ft and 27% at 14,000 ft, relative to sea level. This situation would necessitate a specially designed respirator or rebreather. Compressed air tanks containing these mixtures could not be used at sea level due to the enriched atmospheres.

Thus far, discussion has considered oxygen-deficient atmospheres. Oxygen-enriched atmospheres also pose considerable hazard, for the reason of enhanced ignitability. In the average circumstance, the hazard of enrichment seems to be related to use of oxygen in flame-cutting processes, namely oxy-fuel equipment. Oxygen also could be present in confined spaces where it is generated for use as a process gas. Some work occurs under pressurized atmospheres. In these situations, pressurization increases the partial pressure of oxygen above that found under normal circumstances.

Barometric pressure increases with depth. The Dead Sea, the lowest surface feature on earth is situated at -1337 ft (-408 m). Partial pressure of oxygen at this depth corresponds to a concentration of 22% at sea level. Some deep mines exceed 1 mile (1.6 km) in depth below sea level. Oxygen partial pressure at these depths easily could exceed the partial pressure of 23.5% used in many regulatory limits.

Based on standard total atmospheric pressure associated with the standard (dry) atmosphere and 23.5% as a legal limit, oxygen enrichment would occur at a depth of -2871 ft (-875 m), based on standard atmospheric pressure. However, atmospheric pressure can vary in a location from hour to hour and usually from day to day.

During a period of typical low pressure at this depth, the atmospheric pressure easily could decrease from 853 mm Hg to 853 - 32 = 821 mm Hg. This would decrease the oxygen concentration from 23.5% to 821/760 x 20.95% = 22.6%, relative to sea level. Under this weather condition, this depth would not be oxygen-enriched. During a period of typical high pressure at this depth, the atmospheric pressure would increase from 853 mm Hg to 853 + 28 = 881 mm Hg. This would decrease the oxygen concentration to 881/760 x 20.95% = 24.3%, relative to sea level. Under this weather condition, oxygen-enrichment would be more severe compared to the standard atmosphere. An unusual high pressure system would further exacerbate the condition of oxygen-enrichment.

It could be argued that the true depth at which oxygen enrichment should be considered to occur would be that whose normal high pressure would be 853 mm Hg. This would correspond to a standard atmospheric pressure of 853 - 28 = 825 mm Hg and a depth of -2276 ft (-694 m).

The second approach would be more protective, since this would minimize the chance that oxygen enrichment could occur due simply to variation in atmospheric pressure. Adoption of this approach would permit use of an instrument that is altitude and weather independent.

The preceding is one approach to this problem. Another is to incorporate all gains in partial pressure of oxygen. These would include depth, weather pattern and local atmospheric contamination caused by the work to be performed. This approach would require an instrument responsive to both altitude and weather conditions. Calibration would occur at sea level during an average day. Using this approach, hazard assessment could be subjected to day-to-day variability, as weather conditions and local contamination changed. This would be an especial concern at depths where partial pressures would be close to oxygen-enriched conditions and where weather conditions alone could necessitate control measures.

Issues, Realities, Applications and Opportunities in Oxygen Measurement

Widespread availability of instruments containing oxygen sensors provides the opportunity to gain real-world experience in measuring oxygen. This extends the discussion considerably beyond the abstract of the table-top exercises discussed above.

The first reality is that oxygen has become very easy to measure. Older instruments typically were used just prior to entry into a confined space and periodically thereafter. The instrument was turned on for the measurement and then turned off. Hence, the measurement of the environment in the space thus was relative

to the environment of the external surroundings at that moment in time.

The second reality is the means with which oxygen measurements now occur. Newer instruments can operate during the duration of the workshift and simultaneously measure other gases, such as carbon monoxide. At the same time, these instruments read oxygen level continuously. Some of the instruments contain a datalogger and store the measurement after predetermined intervals of time. These instruments were available at the time of the decision by OSHA to adopt 19.5 % as the regulatory limit and have become widely so during the intervening years.

An issue identified during continuous, shift-length measurement of oxygen is the baseline of the ambient oxygen level. Continuous operation of the instrument establishes an absolute level of oxygen compared to the relative one mentioned above and in previous discussion. Some instruments set the reference level of oxygen at start-up, while the operator can set the reference point of the others at any time, simply by pushing one or more buttons.

Actual workplace monitoring that accumulated 30,000 minutes of oxygen dosimetry during argon-shielded welding in the construction of large aluminum vessels (ships) indicated that the oxygen level is relative and not constant. The level of oxygen often decreased from 20.9% to a constant lower level as low as 20.6% on some days and increased to a constant upper level as high as 21.5% on others. This shift in baseline level appears to depend on weather conditions. The baseline decreased on days when rain was falling at the time of start-up and setting of the oxygen level and changed to sunny conditions later in the day. On days where the weather changed from sunny to rainy conditions during the day, the baseline is presumed to have increased.

Where actual contamination is present, depression of oxygen from the normal level of 20.9% indicates the presence of another substance. The true concentration of the other substance is (20.9 - x)(100/20..9), where x is the reading of the instrument. (The oxygen sensor detects only one molecule out of every five in the atmosphere.) This depression in the oxygen level constitutes extremely important information.

Depression of oxygen to any level below 20.9% is functionally legal only in vary narrow circumstances. These include atmospheres enriched in nitrogen, atmospheres containing high levels of water vapour, mist or steam, and atmospheres containing the chemically inert gases (in practical terms, helium and argon). In all other situations there is reason to account for the substance(s) that depressed the oxygen for compliance with a regulatory exposure limit, for concerns regarding ignitability, or for toxicology that is unknown. This reality also opens the bigger question of setting the oxygen baseline prior to obtaining a reading in an atmosphere containing otherwise undetectable contamination

The issue here is the coincident insensitivity of other sensor(s) to the presence of the displacing or diluting gas or vapour. The depressed reading on the oxygen sensor could be the only indication that conditions are abnormal. That is, depression of the oxygen reading indicates the presence of some other agent at a level that poses concern .The identification and quantification of that agent are paramount to ensuring the continuing safety of workers affected by the reading.

This reality argues that the alarm of the oxygen should be set as close as possible to the ambient value of 20.9%, regardless of its lack of physiological significance. Experience gained with weather conditions, as described previously, indicated that an alarm setting of 20.5% for the oxygen sensor will not incur undue false positive alarms under ambient conditions of continuous operation.

The reality in many industries is that the reading of the oxygen sensor during work in confined spaces in which ventilation is occurring is almost always 20.9%. This almost always was the case during the ship construction, mentioned previously, in which argon was used as a shield gas during welding. No alarms occurred at 19.5% and alarms at levels below 20.5% were highly unusual and only very brief in duration. Alarms at the upwardly revised set-point in this particular example indicated lack of control over welding emissions or leakage of shield gas.

Why not then take advantage of normalcy to indicate abnormalcy? As a follow-up to this comment, the number of simple asphyxiants has decreased considerably in recent years with the adoption of Threshold Limit Values for many formerly included gases (C_1 to C_4 aliphatic hydrocarbons, in particular). In most industrial situations, there is nothing to be gained from using the current regulatory limit of 19.5%.

Despite all of the debate about acceptable limits, the reality is that people live and work over a wide range of altitudes. Healthy people live long and active lives at high altitudes where arterial saturation ranges from 85% to 95 %.

Oxygen deficiency and oxygen enrichment create a fundamental dilemma for the practicing industrial hygienist. One the one hand, exposure to an atmosphere containing a narrow range of concentration is essential for survival. Controlling or eliminating exposure through active intervention is not an option. Conversely, not permitting exposure beyond normal atmospheric concentrations, regardless of the wider range of permissible concentration is a conservative strategy. On the other hand, hygienists sanction exposure of workers to contaminants at nonzero concentrations. The question is whether oxygen deserves special consideration because of our relationship with it and the acute nature of action under hazardous conditions.

Glossary of Terms

ACGIH = American Conference of Governmental Industrial Hygienists

ANSI = American National Standards Institute

ASSE = American Society of Safety Engineers

CSA = Canadian Standards Association

mm Hg = millimetres of mercury (Hydrargium = Hg); the normal height of a mercury barometer at sea level is 760 mm

NASA = National Aeronautics and Space Administration

NFPA = National Fire Protection Association

NIOSH = National Institute for Occupational Safety and Health

OSHA = Occupational Safety and Health Administration

ppm = parts per million, a unit of concentration in air

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