UCRL- 95544
PREPRINT

UCRL--95544

DE87 012911

ALARM POINTS FOR FIXED OXYGEN MONITORS

Gordon C. Miller

This paper was prepared for presentation to the American Industrial Hygiene Conference, Montreal, Canada, June 1-5, 1987

May 1987

Lawrence Livermore Laboratory

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ALARM POINTS FOR FIXED OXYGEN MONITORS*

by Gordon Miller

Abstract

Oxygen concentration monitors were installed in a vault where numerous pipes carried inert cryogens and gases to the Mirror Fusion Test Facility (MFTF-B) experimental vessel at Lawrence Livermore National Laboratory (LLNL). We reviewed the problems associated with oxygen-monitoring systems and the reasons why such monitors are installed. As a result of this review, the MFTF-B monitors were set to sound an evacuation alarm when the oxygen concentration fell below 18%. We chose the 18% alarm criterion to minimize false alarms and to allow time for personnel to escape in an oxygen-deficient environment.

INTRODUCTION

An "oxygen-deficient atmosphere" contains less than 19.5% oxygen, as stated in the standard for open surface tanks promulgated by the Department of Labor under the Occupational Safety and Health Act (OSHA) of 1970.[1] While planning the installation of oxygen-deficiency sensors and alarms in a large

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

vault housing the MFTF-B magnetic-confinement fusion experiment, the question arose as to whether 19.5% oxygen was suitable as the level to sound evacuation alarms. Thousands of gallons of liquid nitrogen and liquid helium were to flow from nearby liquefication plants into and out of the vessel to cool superconducting magnets. Fortunately, during the planning stage for the installation of oxygen monitors in the MFTF-B vault, the Hazards Control Safety Science Group was conducting its own experiments to define how meteorological variables can affect the operation of common electrochemical oxygen monitors. The considerations that went into deciding the oxygen level at which an evacuation alarm should sound are discussed below.

PHYSIOLOGICAL CONSIDERATIONS

The partial pressure of oxygen in a gas mixture--the actual number of oxygen molecules present in the gas--can be calculated by multiplying the barometric pressure of the mixture by the volumetric percentage of oxygen in it. In the case of air at sea level, the partial pressure of oxygen is 20.9% of atmospheric pressure (760 mm Hg), or 159 mm Hg. Deep-sea divers rely on the distinction between the partial pressure of oxygen and the percentage of oxygen in their breathing air; a diver's air tank holds gas mixtures at elevated pressures that contain very small volumetric percentages of oxygen.

It is well reported that people can tolerate breathing air in which the volumetric oxygen concentration exceeds 16% without ill effects.[2,3] As can be seen in Table 1, people develop progressively more serious symptoms as the oxygen concentration decreases below 16% until death occurs when the oxygen concentration reaches 6%. The alveolar partial pressure gives a measure of how much oxygen is actually available to the body. The alveolar partial pressure of oxygen can be estimated using the following formula:[4]

$$P_a = F_i(P_b - 47) - P_c \quad F_i + \frac{1 - F_i}{0.85}$$

where

F_i = Volumetric oxygen percentage in the air being breathed.

P_b = Barometric pressure of the atmosphere being breathed.

P_c = Alveolar partial pressure of CO_2 (about 40 mm Hg).

It can be shown that the alveolar partial pressure of oxygen at a high altitude, such as in Denver, from air with an oxygen concentration of 19.5% is below the alveolar partial pressure at sea level, such as in San Francisco, from air with an oxygen concentration of only 16%.[2] It should be noted that people do acclimate to altitudes up to 6000 feet.[2] However, an engineer from San Francisco visiting a job site in Denver for a day, for example, would not have a chance to acclimate to the higher altitude.

OXYGEN MONITORING

While a variety of measurement methods are available for measuring oxygen concentrations in air,[5] only electrochemical sensors are commonly used to measure the oxygen content of breathing air. In an electrochemical sensor, a pair of electrodes is immersed in an electrolyte in a chamber, as shown in Fig. 1. One end of the chamber is open, but covered with a membrane through which oxygen can diffuse into the electrolyte. Oxygen dissolved in the electrolyte drives a chemical reaction that generates a current proportional to the volumetric concentration of oxygen in the air. Oxygen in the cell is expended to drive the reaction, thereby reducing the oxygen concentration in the electrolyte. This creates a diffusion gradient that causes more oxygen to pass through the membrane. In order to operate the detector, it is necessary only to connect this electrochemical cell to a meter and ensure that fresh air always flows over the membrane. The concentration of oxygen in fresh air is always 20.9% by volume, so the instrument is calibrated by drawing fresh air past the sensor and the output is adjusted to read 20.9%. While there are variations in cell design and chemistry, the description given above applies to virtually every electrochemical oxygen instrument.[6]

Unfortunately, an electrochemical oxygen monitor actually responds to the number of molecules of oxygen in the electrolyte--i.e., the partial pressure of oxygen.[5] It can be predicted that a change of barometric pressure changes the partial pressure of oxygen, and so the indicated concentration will change even while the volumetric oxygen concentration remains at 20.9%. Thus a calibration made at 20.9% volumetric oxygen concentration will be valid only at the barometric pressure when the instrument was calibrated. The evaluations of oxygen monitors mentioned elsewhere in this paper were prompted by false alarms received by the LLNL Fire Department when weather fronts passed by the Livermore site.

Note also that the electrochemical reaction rate increases as temperature increases. Existing instruments include temperature sensors colocated with the electrochemical cells to provide for automatic temperature compensation[5] so that changes in ambient temperature will not cause erroneous readings, but a difference of temperature between them can still cause an improper indication. We can speculate that the temperature may change rapidly in a small temperature sensor, whereas the aqueous electrolyte in the cell will compensate more slowly. This temperature-adjustment difference will cause the sensor and cell temperatures to diverge and, therefore, lead to erroneous readings. Another cause of erroneously low readings is if a water film were present on the membrane. This would profoundly reduce the amount of oxygen presented to the membrane, allowing almost no permeation to drive the cell.

Swearengen et al. of the Safety Science Group at LLNL conducted tests of climatic variables on oxygen monitors (some of their findings shown in Figs. 3, 5, and 6 of Ref. 7). They found that increasing relative humidity (RH) or decreasing barometric pressure reduced the indication of two types of electrochemical oxygen sensors even though volumetric oxygen concentrations remained constant. One sensor responded to temperatures that gradually dropped about 10C over three hours by progressively overindicating oxygen concentrations (by about 1%) and returning to the nominal reading when the temperature was returned to the initial value over the next hour. A sensor from another manufacturer overindicated by about a half percent for nearly 30 minutes while temperatures decreased, and then properly indicated oxygen concentrations until temperatures began rising again, at which time it underindicated oxygen concentrations. In another test, oxygen monitors were placed in a building and their outputs recorded for six days. Readings fluctuated through a range of about 1%.

The results of Swearengen et al. suggest why the LLNL Fire Department received false alarms when the weather changed. Meteorological conditions can be regarded as variables fluctuating about mean values that change over time; then it can be seen that reducing the volumetric oxygen concentration at which an electrochemical monitor alarms should also reduce the number of false alarms. It can also be predicted that rapid rates of pressure or temperature change should trigger more false alarms.

REGULATORY CONSIDERATIONS

OSHA states in 29CFR 1910.94 (d) (1):

"When, during emergencies as described in paragraph (d) (11)(v) of this section, workers must be in areas where concentrations of air contaminants are greater than the limit set by paragraph (d)(2)(iii) of this section, or oxygen concentrations are less than 19.5%, they shall be required to wear respirators adequate to reduce their exposure to a level below these limits, or to provide adequate oxygen."[1]

This paragraph specifies the minimum oxygen content of breathing air as a volumetric percentage. It is not a specification of when monitoring devices are to warn of insufficient (or excessive) oxygen content. This is important because many fixed-point oxygen-monitoring systems, including the one considered here, are not installed to assure that local breathing air has more than 19.5% oxygen; instead, these systems sound alarms warning people to leave places where the air is becoming dangerously deficient in oxygen due to an unusual occurrence (such a cryogen spill or a leak of inert gas). It is assumed that the oxygen concentration will remain close to 20.9% until an unusual incident occurs, and the chance is insignificant that biological or chemical processes will gradually reduce oxygen concentrations below 19.5%.

The strict OSHA specification for oxygen deficiency has an important aspect when considering where to set an alarm level. Many oxygen deficiencies, including those that could occur in the MFTF-B vault, will probably develop quickly. The volumetric percentage (and partial pressure) of oxygen will rapidly drop from 20.9% and 159 mm Hg (at sea level) to much lower levels when a leak or vapor cloud creates an expanding volume of oxygen deficient gas. The level at which an alarm is set will influence the time in which people can escape before the atmosphere becomes hazardous. An alarm point set closer to the normal atmospheric content of oxygen will sound the alarm earlier and give more escape time than an alarm point set further away from the normal atmospheric content of oxygen. An alarm point set close to atmospheric content will also, however, be more prone to false alarms.

It is noted that the effects of altitude are not explicitly mentioned. This is not the only oxygen-concentration limit specified in Federal and other standards, including OSHA regulations. Some of the other oxygen-deficiency limits are specified in Table 2.[2]

BEHAVIORAL CONSIDERATIONS

It has been shown, both from the theory of how electrochemical oxygen sensors operate and by experimental results, that meteorological variables can easily cause false alarms. False alarms are not just an annoyance for a fire department or maintenance personnel: they are a technological case of the "boy who cried wolf." Too-frequent alarms can cause workers to pay less attention to an oxygen-deficiency alarm and either evacuate slowly or not bother to evacuate at all (as has happened in at least one case away from LLNL). Serious consequences could occur from this attitude if the alarm is real.

CONCLUSIONS

We drew the following conclusions for the purposes of installing oxygen monitors in the MFTF-B vault:

1. This system is intended to warn people of dangerous oxygen deficiencies, not to monitor compliance with the 19.5% OSHA definition of "oxygen deficiency."

2. Permanently installed oxygen monitors are prone to false alarms. Swearengen's data objectively confirm theoretical predictions that barometric and temperature changes will cause the indications of oxygen meters to change.

3. LLNL is at a low altitude, and it is therefore not necessary to have a volumetric oxygen concentration of 19.5% to sustain life, or even to maintain productivity or avoid any type of ill-effect.

4. If the system experienced a high false-alarm rate, we found a real danger that persons working in the MFTF-B vault would not react to oxygen-deficiency alarms in a timely manner or would ignore them.

5. Setting the alarm point at a volumetric oxygen percentage of 19.5% will increase the probability of false alarms; conversely, setting the alarm point at a lower concentration decreases the escape time in an emergency. The alarm point for the MFTF-B oxygen monitors needed to be set at a level that balanced a longer escape time against the probability of false alarms.

It was recommended that oxygen-deficiency monitors be installed and that alarm points be set at a volumetric oxygen concentration of 18%. This concentration is used as the minimum-oxygen-content criterion in the widely respected Threshold Limit Value lists,[8] and represents the best compromise between minimizing false alarms and maximizing the time for escape.

OPEN ISSUES

The most commonly used definition of oxygen deficiency, 19.5% by volume, is not well suited for use as an alarm point and also warrants reconsideration as the definition of an oxygen-deficient atmosphere.

The evaluation described in this paper suggests that the following matters need further consideration:

1. What is a "safe" oxygen concentration for acclimated and unacclimated people at various altitudes? This matter is well addressed in the contexts of aviation, astronautics, and aquanautics, and should also be investigated in the contexts of average working populations and industrial workers.

2. What are the effects of concurrent exposures to oxygen-deficient atmospheres and oxygen-depriving substances such as carbon monoxide, methylene chloride, or aromatic nitrates and amines? It may be possible to set better standards for oxygen deficiencies and action limits for evacuation.

3. Can electrochemical oxygen monitors be modified or replaced by a different operating system so that such monitors will measure volume percentages instead of partial pressures? Such instruments should be intrinsically more resistant to false alarms. City Tech of London has developed a sensor with a capillary section that makes it far less sensitive to barometric pressure fluctuations than conventional sensing. Thus it might be possible to set the alarm point at OSHA's 19.5 per cent without having to worry about false alarms. Since the Bureau of Mines evaluation was very favorable,[9] LLNL has purchased a portable instrument from Neotronics that contains this sensor. Another manufacturer replaced a conventional sensor and automatic barometric pressure compensation with a Neotronics sensor. Delta F has developed a sensor with nonconsumable electrodes and electrolyte. This minimizes the drift caused by sensor deterioration and thus reduces the need for periodic calibrations of the system[10]. The electrodes are porous and this creates a capillary effect that also makes the Delta F sensor resistant to changes in barometric pressure[11]. Another project at LLNL selected Delta F for their fixed oxygen deficiency monitoring system. Both Neotronics and

Delta F sell instruments with dual alarm points. We advise users to set the higher alarm point at 19.5% to act as a local action alarm and set the lower alarm point at 18% to act as an urgent action alarm that is also transmitted to the Fire Department.

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Table 1. The effects of oxygen deficiency.[3]

Sea-level volumetric oxygen concentration (%)	Physiological effect
16 - 12	Increased breathing volume; Accelerated heartbeat; Impaired attention and thinking; Impaired coordination.
14 - 10	Very faulty judgment; Very poor muscular coordination; Muscular exertion causes rapid fatigue that may cause permanent heart damage; Intermittent respiration.
10 - 6	Nausea and vomiting; Inability to perform vigorous movement or loss of all movement; Unconsciousness, followed by death.
Less than 6	Spasmatic breathing; Convulsive movements; Death in minutes.

Table 2. Definitions of oxygen deficiency. Note that even the Code of Federal Regulations has not agreed to a consistent definition.

Source	Volumetric oxygen concentration (%)	Conditions for determination	Sea-level partial pressure of oxygen (mm Hg)
29CFR 1910.94	19.5	--	148
29CFR 1910.134	16.0	--	122
29CFR 1915.81	16.5	--	125
30CFR 11	19.5	"By volume at sea level"	148
NIOSH Criteria Document for Working in Confined Spaces	19.5	At sea level (Class C space)	148
	16.1-19.4	At sea level (Class B space)	122-147
	16 or less	At sea level (Class C IDLH space)	122 or less
ANSI Z117.1-1977	18	--	137

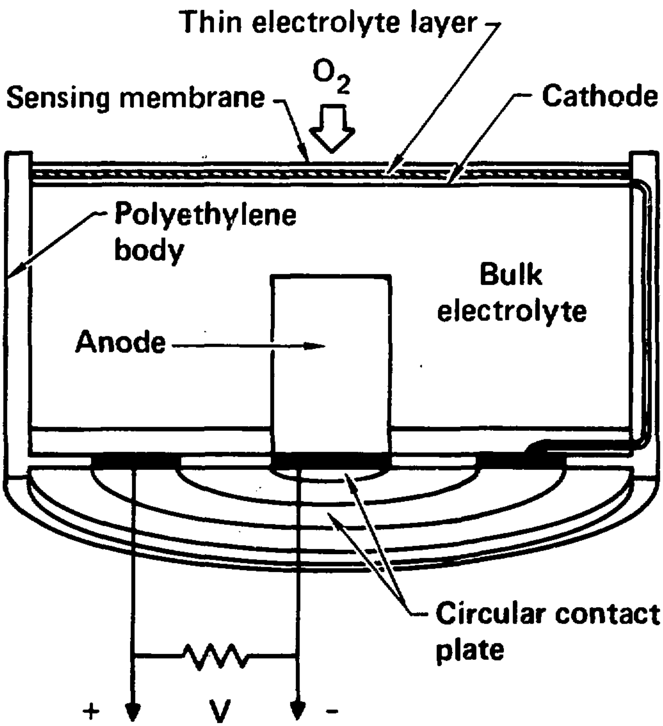

Figure 1. A typical electrochemical fuel cell used in oxygen-deficiency monitors.

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