Oxygen Levels During Welding

Assessment in an Aluminum Shipbuilding Environment

By Neil McManus and Assed N. Haddad

Oxygen deficiency is a well-recognized cause of death in confined spaces (OSHA, 1985), a fact that motivated regulatory action by OSHA (i.e., 29 CFR 1910.146, 29 CFR 1915, Subpart B). Oxygen deficiency can occur through only a limited number of mechanisms that may or may not apply in a specific situation (McManus, 1999). These mechanisms include oxidation of metal surfaces, aging of reactive surfaces through oxidation, respiration by microorganisms, offgassing of large quantities of vapor or gas from surfaces and vapors from liquids, and adsorption by reactive surfaces. These actions dilute and/or displace the existing atmosphere.

IN BRIEF
- **Oxygen deficiency is a major concern during use of inert gases such as argon and helium for shielding welding arcs. Large aluminum structures created during shipbuilding have complex geometries that may trap shield gas at ambient temperature and in the hot plume.**
- **This article reports on nearly 15,000 minute-by-minute measurements of oxygen using portable sampling instruments worn by workers to determine the potential for oxygen deficiency relative to the commonly used regulatory limit of 19.5%. Almost all readings exceeded 20.5%.**
- **The results support ongoing use of continuous monitoring instruments to detect situations not anticipated in the work plan because oxygen-deficient conditions often lack warning properties.**

While these reactions can occur in the open, they are considerably more likely to occur in confined spaces where enclosure prevents interaction with the normal atmosphere. Experience has shown that oxygen deficiency can develop prior to entry into confined spaces or as a result of work activity in the space (NIOSH, 1979, 1994; OSHA, 1985).

That situation occurred at a shipyard in Vancouver, British Columbia, during fabrication of aluminum vessels by arc welding. The shipyard is located at sea level. Welding occurred under open, partially and semi-enclosed, and completely enclosed conditions. Structures created during fabrication have geometries ranging from simple to complex. Pure argon or blends containing 25% helium/75% argon (He/Ar) are shield gases used in gas metal arc welding, also known as metal inert gas welding processes (Althouse, Turnquist, Bowditch, et al., 1988). These processes are used extensively during tacking and fitting, and robotic and manual production welding involving aluminum.

A puff or cloud of pure argon at room temperature is about 1.4 times as dense as air based on the ratio of the atomic and molecular weights (Haynes, 2001). As a result, a puff or cloud of pure argon or He/Ar versus a dilute mixture in air at ambient temperature tends to settle to or remain at a structure's lowest level. Ventilation modeling has demonstrated that pooled clouds of dense gas or vapor located at the bottom of structures are extremely difficult to disperse (Garrison & Erig, 1991).

Displacement or dilution of oxygen by argon in work spaces is distinctly possible in the absence or inefficient use of supply and/or exhaust ventilation systems. During welding, a welder's face is close to the flow of shield gas; this applies regardless of whether the welding process is manual or automated. Shield gas can accumulate in work spaces or adjacent spaces. Possible sources include leakage from a valve in the manifold, a supply hose, an open-ended line or a welding gun. Emission from welding guns occurs during purging, wire feeding and welding.

Shield gas flows through the gun whenever the trigger is activated, regardless of whether welding

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is occurring. Based on settings used by welders in the facility in the study, gas flows at 22 L/min (about 1.5 m/s through the opening in the gun). This rate of flow is needed to maintain the bubble of gas above the metal prior to and during welding.

Welders routinely released argon into the atmosphere during purging of hoses from the piped-in supply to the welding machines and from them to the welding guns, and preconditioning the zone at the position of the weld prior to striking the arc.

To determine the potential for oxygen depression and deficiency during this work, bench-scale testing was conducted. Bench-top testing in the absence of the arc showed depression of oxygen by argon from 20.9% to 20.1% during this type of activity. The depression was brief and recovery to the normal level of 20.9% was rapid. This testing also showed the critical nature of the geometric relationship between the welder's nose, boundary surfaces formed by the metal and the rate of delivery of argon from the welding gun.

During welding, the plume rises to the highest level in the airspace of the structure under the influence of buoyant forces. This occurrence is readily observable. Confinement of the plume in structures containing overhead panels or during overhead work occurs in the absence or inefficient use of supply and/or exhaust ventilation systems. Argon or He/Ar heated to high temperature in the welding arc is presumed to rise with the plume of particulates.

Welding occurs in three geometric modes: 1) downward onto lower horizontal surfaces; 2) upward and downward on vertical surfaces; and 3) upward onto horizontal overhead surfaces. The welder interacts naturally with the plume in different ways during work in each mode.

During welding downward onto lower horizontal surfaces, the plume passes up the upper chest, around the neck and up the back of the head or remains in front of the welder. During welding on vertical surfaces, the plume moves up the vertical surface of the metal in front of the welder. During welding overhead, the plume moves along the surface of the metal and can become trapped by vertical downward protrusions. Entrapment can cause immersion of the welder's face in the plume.

While the presence of argon or He/Ar in the atmosphere inside structures during arc welding can cause oxygen deficiency, the magnitude of this concern is not discussed in the literature. Oxygen deficiency at normal atmospheric pressure results from displacement and/or dilution of molecules in the normal atmosphere by molecules that produce no physiological effect in the body (ACGIH, 2013). Chemically inert gases such as argon and helium coexist with atmospheric molecules (including nitrogen and water vapor) without a chemical reaction occurring between them. Thus, the normal atmospheric concentration of oxygen may be diluted by any gas, and the physiological effects of the resulting oxygen deficiency are independent of the specific gas causing the dilution. That is, one or more types of molecule singly or in simultaneous combination can cause the same effect. The effect is due solely to the availability of oxygen molecules in the atmosphere.

Welding occurred under open, partially and semi-enclosed, and completely enclosed conditions. Structures created during fabrication had geometries ranging from simple to complex.

The concentration of oxygen in dry air at sea level is 20.9%. The corresponding pressure of oxygen is 159 mm Hg (millimeters of mercury) compared to the total normal atmospheric pressure of 760 mm Hg or 101 kPa. In normal humidified air, the pressure and, therefore, concentration of oxygen are slightly less due to the presence of water vapor to maintain constant total pressure (Lide, 2006).

The study of oxygen deficiency is complicated by the manner in which the body responds (Küpper, Milledge, Hillebrandt, et al., 2011; Miller & Mazur, 1984; NIOSH, 1976). The body responds to the pressure of oxygen, rather than the concentration. The composition of air (percentage of each gas) remains the same with increasing altitude. At the same time, the atmosphere's pressure and, hence, the partial pressure of oxygen and the other gases decrease with increasing altitude. Lide (2006) provides tables of total and partial pressure of gases in the atmosphere at different altitudes.

Table 1 (p. 28) summarizes the effects of acute exposure to oxygen-deficient conditions, as commonly reported (Miller & Mazur, 1984; NIOSH, 1976). The rate of onset of the symptoms listed depends on many factors, including breathing rate, work rate, temperature, emotional stress, age and individual susceptibility. These factors can exacerbate the effects of an oxygen-deficient atmosphere and influence the onset, course and outcome of incidents that occur under these conditions.

The physiological basis for immediately dangerous to life or health (IDLH) for oxygen deficiency is an atmosphere that causes an oxygen partial pressure of 100 mm Hg of freshly inspired air that is saturated with water vapor in the upper portion of the lung. This corresponds to 90% saturation of hemoglobin and concentration of oxygen in air at sea level of 14% (Miller & Mazur, 1984; NIOSH, 1976). The regulatory limit for oxygen deficiency has varied over the years from 16% to 19.5% (McManus, 1999). Most jurisdictions today use 19.5%.

The regulatory limits present a floor, rather than a time-weighted average (TWA). Instructions concerning interpretation are not usually provided. The context of a floor means that a brief or even an instantaneous excursion below the level would violate the limit. The floor used by NIOSH (2005) for respirators that do not supply air from an exter-

Table 1

Effects of Acute Exposure to an Oxygen-Deficient Atmosphere

Effect	Concentration (%)	Atmospheric oxygen pressure (mm Hg, dry air, sea level)
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	< 12	< 76
Convulsions, shortness of breath, cardiac standstill, spasmatic breathing, death in minutes	< 6	< 46
Unconsciousness after one or two breaths	< 4	< 30

nal source is 19.5%. A decrease of oxygen below 19.5% is below the approved limit for the respirator. By contrast, OSHA (1998) allows the use of any atmosphere-supplying respirator at sea level (the location of the shipyard in this study) where the employer can demonstrate that the concentration of oxygen is at least 16%.

As shown in Photos 1 and 2, the datalogging instrument was taped into the upper pocket of coveralls and the remote sampling probe was positioned on the top of the shoulder. In this location, the device is protected and the alarm is easily heard.

Study Methods

Oxygen levels were measured in the breathing zone of welders using standard confined space testing instruments that contained a datalogging function and internal pump. According to the manufacturer, the instruments have no restriction for long-duration operation in this type of service. The instruments contained fuel-cell oxygen sensors, which operate on the basis of lead reduction by atmospheric oxygen (Chou, 1999). Of the two types available, the instruments contained partial-pressure oxygen sensors, which have a relatively large opening into the interior that is covered by a diffusion barrier (City Technology). This opening readily allows diffusion of gases from the atmosphere. This type of sensor is sensitive to changes in barometric pressure and altitude. By comparison, the capillary oxygen sensor contains a channel of small diameter in the top of the sensor (City Technology). This type of sensor measures concentration of oxygen; its small opening compared to the large surface in the partial-pressure sensor can influence response time.

T_{90} and T_{95} are standard measures of the time required for the sensor to reach 90% and 95% of full response, respectively. T_{95} published for the oxygen sensor of the type used in this instrument is ≤ 15 seconds and for a typical capillary sensor < 20 seconds (City Technology). The value of T_{95} for the partial-pressure sensor is small compared to the sampling interval of 1 minute.

The manufacturer specifies repeatability of ± 2% for the sensors; accuracy is 0.5% by volume for the oxygen sensor and ± 10% of the reading for the other sensors. The instruments were calibrated according to the manufacturer's instructions.

During the start-up sequence, the instruments set the benchmark for oxygen concentration (20.9%) and the zero point for the other sensors. This means that the instruments accept air containing varying levels of moisture and barometric pressure as having 20.9% oxygen. The partial pressure of water vapor is about 10 Torr at normally encountered temperatures. This also reflects moisture content in the air, especially when rain is falling and rapidly drying. A typical high-pressure system adds about 28 Torr and a typical low-pressure system removes about 32 Torr from the total atmospheric pressure.

Normal atmospheric pressure at sea level (the shipyard's location) is about 760 Torr (Moran & Morgan, 1989). Therefore, start-up occurred in an environment known to contain the normal level of oxygen (20.9%). This was the case outdoors and in buildings where argon use and welding were not occurring.

The instruments were taped into the upper pocket of coveralls and the remote sampling probe was positioned on the top of the shoulder (Photos 1 and 2). These instruments contain a continuously operating, built-in sampling pump. The number of samples obtainable on a particular day depended on the availability of volunteers, the structure's geometry and weld orientation. The goal was to take the greatest number of representative samples obtainable within the time available for this work.

The instrument's data-processing circuit samples the signal from the oxygen sensor every 3 seconds and temporarily stores the lowest value in memory. At the end of each 1-minute interval, the circuit transfers this value for retention in the datalogger. One minute is the smallest value of the user-selected interval, while 5 minutes is the longest value. A warning alarm sounds when the oxygen level decreases to 19.5% or less. The datalogger provides minute-by-minute records for the sample period in chronological sequence during download.

The regulator in British Columbia requires employers to assess work conditions. This assessment required cooperation and active participation from welders and other shipyard workers. Everyone who participated was a volunteer and gave informed consent.

Prior to beginning the sampling, each prospective participant received a brief explanation about the instrument and what information it creates and stores. Anyone uncomfortable with participation was excused without repercussion. No names were recorded. Participation varied considerably from one session to multiple sessions depending on individual comfort in wearing the equipment and interest.

Study Results

Tables 2 and 3 (p. 30) summarize 14,586 minute-by-minute records of breathing-zone measurements of oxygen obtained on welders engaged in manual and robotic production welding. Table 2 presents results from various activities while Table 3 presents results from work on the engine bed, a large, inverted structure that required overhead welding inside the space formed by the engine girders and the bottom sheet. Supply and local exhaust ventilation were provided at all times during this work.

The tables summarize the data from each sample normalized to percentage of readings that occurred at each concentration during the measurement period. Normalizing provides a common basis for comparing all samples within a group since the duration of sampling differed, in some cases considerably.

Table 2
Oxygen Levels Measured on Production Welders, Various Activities

Dur.	Low value	Percent of time at different oxygen concentrations in intervals of 0.1%																
		19.5					20.0					20.5					21.0	
Center module wet deck, Ring 3, natural ventilation																		
135	A	---	---	---	---	---	---	---	---	---	1	4	12	23	45	14	---	---
Center module wet deck, Ring 3, supply and local exhaust ventilation																		
412		---	---	---	---	---	---	---	---	---	---	---	1	10	36	46	7	---
169		---	---	---	---	---	---	---	---	---	---	1	10	53	37	---	---	---
370		---	---	---	---	---	---	---	---	< 1	< 1	1	2	6	50	38	2	---
376		---	---	---	---	< 1	< 1	< 1	< 1	1	4	5	14	34	39	< 1	---	---
104		---	---	---	---	---	---	---	---	---	1	---	2	5	23	51	18	---
440		---	---	---	---	---	---	---	---	< 1	< 1	< 1	5	22	43	23	5	---
157		---	---	---	---	---	---	---	---	---	---	---	---	4	27	63	6	---
144		---	---	---	---	---	---	---	3	3	8	10	9	8	24	36	---	---
Frames, Ring 3 and 4, bottom surfaces, supply and local exhaust ventilation																		
130		---	---	---	---	---	---	< 1	2	2	2	< 1	3	5	25	41	19	---
380		---	---	---	---	---	---	---	---	---	---	< 1	3	35	56	5	---	---
405		---	< 1	< 1	< 1	---	< 1	< 1	1	2	3	2	7	24	37	22	---	---
380		---	---	---	---	---	---	---	---	---	---	---	< 1	23	69	8	---	---
399		---	---	---	---	---	---	< 1	---	---	< 1	3	7	23	40	26	< 1	---
382		---	< 1	---	---	---	< 1	< 1	< 1	3	8	12	29	32	8	4	---	---
262		---	---	---	---	---	---	---	---	---	< 1	3	7	36	49	5	---	---
266		---	---	---	---	---	---	---	< 1	< 1	1	< 1	2	14	41	42	---	---
354		---	---	---	---	< 1	---	< 1	1	2	3	10	14	15	29	20	4	---
357		---	---	---	---	---	---	---	---	---	---	< 1	3	19	52	26	---	---
353		---	---	---	---	---	---	---	---	---	---	1	4	13	42	37	2	---
Frames, Ring 4, vertical surfaces, supply and local exhaust ventilation																		
228		---	---	---	---	---	---	---	---	< 1	< 1	3	11	44	29	11	---	---
370		---	---	---	---	---	< 1	< 1	< 1	< 1	2	2	7	34	51	3	---	---

Note. *Dur. = duration of the sample in minutes; Low value = minimum value recorded by the instrument below 19.5%; A = 17.6% oxygen for < 1% of the sample time.*

Readings were affected by two recognizable systemic influences: loading of the in-line filter by particulates and variation in atmospheric conditions. Several early samples terminated prematurely because of loading of the in-line filter. Typically, the concentration of oxygen in datalogged records started at 20.9% or 20.8%. Most records obtained under various conditions equaled or exceeded 20.5%.

In some cases, the baseline (level of oxygen reported by the instrument) decreased gradually to a lower level and returned to 20.9% at the end of the sampling period. Readings in these situations appear to reflect the emission and accumulation of argon in the structure or work area. Enclosed or partially enclosed structures were subjected to an active ventilation program involving a worker dedicated to that purpose.

In other situations, the baseline decreased below 20.9% and remained at the new level throughout the day. Typical maximum decrease was 0.3% to 20.6% oxygen. In still other situations, the baseline increased above 20.9% during the day and remained at the new level. Typical maximum increase was 0.5% to 21.4%. The baseline in the latter situations appeared to reflect the influence of atmospheric conditions.

Atmospheric conditions (temperature, pressure and humidity) changed during some of the tests due to passage of weather systems. Hence, the baseline is relative to conditions at the time of start-up. In the event of additional shutdowns and start-ups during the day, as might occur during operations of very short duration, the instrument would adjust the baseline to read 20.9% at the time of each start-up. The baseline shifts as reported here would not have been observable during operation performed in this manner.

In-depth examination of individual records is required to discuss how changes in level occur. However, there is no easy way to present this information other than to provide a summary that condenses the sample to a manageable size. The summary cannot communicate the actual sequence of events as described in the following discussion. The concentration of oxygen in minute-by-minute records was the minimum recorded during the period. The minimum lasted for an unknown fraction of the period of the record. Superimposed onto the baseline level in many samples were excursions characterized by rapid decrease in concentration followed by equally rapid restoration.

The depth of the decrease and the frequency of these excursions reflected the geometry of the environment in which the work was performed. As indicated in Table 3, the most pronounced excursions occurred during overhead welding in the inverted engine bed. Episodes of lesser magnitude occurred during work on horizontal surfaces at the bottom of frames and in enclosed compartments in the center module between the two hulls. Some information indicates that these excursions reflect individual work style. In other words, different individuals performing the same task in the same location at the same time experienced considerably different conditions.

Many excursions contained only one or two values below the baseline, meaning the episode lasted at most 2 minutes. That is, the decrease and subse-

Table 3

Oxygen Levels During Overhead Production Welding in the Inverted Engine Bed

Dur.	Low value	Percent of time at different oxygen concentrations in intervals of 0.1%																
		19.5					20.0					20.5					21.0	
412		---	---	< 1	---	---	---	---	---	---	---	< 1	1	9	27	43	15	4
217		< 1	< 1	2	3	4	4	5	6	6	11	16	23	17	3	---	---	---
80		---	---	---	---	---	---	---	---	---	---	1	6	9	33	49	3	---
379		---	---	---	---	---	---	---	---	< 1	1	1	5	8	57	26	---	---
280		---	---	---	---	---	< 1	< 1	< 1	< 1	1	3	3	9	4	75	3	---
392		---	---	---	< 1	< 1	< 1	< 1	< 1	1	2	3	9	32	39	12	---	---
397		---	---	---	---	---	---	---	---	---	---	< 1	---	---	4	30	64	2
383		---	---	---	---	---	---	---	< 1	---	---	2	2	19	49	28	---	---
363		---	---	---	---	< 1	---	< 1	< 1	< 1	< 1	< 1	13	43	39	2	---	---
356		---	---	---	---	---	---	< 1	< 1	2	6	8	23	42	19	< 1	---	---
56		---	---	---	---	---	---	---	---	---	---	5	12	59	24	---	---	---
403		---	---	< 1	---	---	---	---	---	---	1	2	8	16	35	36	< 1	---
216		---	---	---	< 1	---	---	---	---	---	< 1	4	18	53	25	---	---	---
407		---	---	---	---	---	---	---	---	---	< 1	2	37	54	6	---	---	---
331		---	---	---	< 1	< 1	< 1	---	< 1	1	< 1	2	2	24	55	14	---	---
359	A	---	< 1	1	3	2	9	6	6	14	13	21	13	7	5	< 1	---	---
352		---	---	---	---	---	---	---	< 1	1	5	7	18	31	30	6	---	---
393	B	---	---	< 1	< 1	< 1	< 1	1	2	1	3	5	5	17	30	32	4	---
399	C	< 1	---	---	< 1	---	---	< 1	---	< 1	< 1	2	5	7	28	46	10	---
402		< 1	---	---	---	---	---	---	< 1	---	< 1	1	2	9	48	37	2	---
382	D	---	---	< 1	< 1	< 1	2	< 1	3	6	16	24	32	13	< 1	< 1	---	---
278	E	---	---	---	---	---	---	< 1	< 1	< 1	1	3	9	39	6	34	4	---
378		---	---	---	---	---	---	< 1	1	4	8	14	17	40	15	< 1	---	---
399		---	---	---	---	---	---	< 1	< 1	1	2	8	10	23	38	17	1	---

Note. *Dur. = duration of the sample in minutes; Low value = minimum value recorded by the instrument below 19.5%; A = 19.1% oxygen for < 1% of the sample time; B = 19.4% oxygen for < 1% of the sample time; C = 19.3% oxygen for < 1% of the sample time; D = 18.7% oxygen for < 1% of the sample time; E = 19.3% oxygen for < 1% of the sample time.*

quent restoration required less than 1 minute each and occurred during two consecutive records. This is evident only from the original records and not from the data presented in Tables 2 and 3, which present a time compression of events.

At face value, the data as presented in the tables create the impression that episodes of markedly decreased oxygen concentration occurred over a prolonged period, but this was not the case. The rapid decrease and equally rapid recovery of the oxygen readings brings forth questions about inherent decay time and autocorrelation on instrument readings. That is, to what extent does the previous reading affect the current reading of the true oxygen concentration? These questions remain unanswered.

During these studies, supply and exhaust ventilation were provided through the efforts of a worker assigned to this purpose. Few welders made any effort to utilize the installed local exhaust system (a low-volume, high-velocity system). This reflected the extreme difficulty in positioning the collector hoods in the appropriate location in a structure fabricated from nonferrous metals. Furthermore, on several occasions, unauthorized individuals moved or shut down portable ventilation fans, which altered or destructed planned airflows. Lack of restoration of oxygen to normal atmospheric levels, as observed in these results, was a direct consequence of these actions.

Eight of the records obtained during this study contained excursions in which the readings were equal to or less than 19.5%. These incidents lasted less than 1 minute. The latter concentration is the floor imposed by NIOSH (2005) and OSHA (1993, 1994, 2014) on respirator selection and ACGIH (2013) in its threshold limit values.

Discussion

NIOSH (2005) defines an oxygen-deficient atmosphere as containing oxygen at a concentration below 19.5% at sea level, and it states that this requirement includes a safety factor. When concentration is below this level, NIOSH recommends using an atmosphere-supplying respiratory protection device. ACGIH (2013) recommends minimal ambient partial pressure of oxygen of 132 Torr (dry air concentration of 17.5%) as protection against inert oxygen-displacing gases and oxygen-consuming processes for altitudes up to 5,000 ft (1,524 m) with additional recommendations for work at higher altitudes.

Interpretation of the excursions from the baseline level of oxygen obtained during this study relative to guidelines and regulatory limits is not straightforward. No discussion for interpreting real-world results against regulatory limits exists in current literature. The real-world meaning of the concept of a maximum (ceiling) or minimum (floor) derives from time requirements of the measurement technique. Most measurements made for comparison against ceiling limits are TWAs and not the near-to-instantaneous values made available by advancements in measurement technology and data storage (NIOSH, 1994, 2003).

For many years, the most rapid technique for assessing concentration was the colorimetric detector tube. These tubes were available for a limited number of substances, including oxygen (Dräger Safety, 2011; Gastec Corp., 2012; Sensidyne, 2005). Colorimetric detector tubes for oxygen provide a short-term TWA over the period of measurement lasting 30 seconds or more depending on the number of pump strokes needed to obtain the sample. Information derived from measurement of oxygen using gas bags for collection and a gas chromatograph or mass spectrometer for analysis depends on sample collection time (An & Joye, 1997; CSA, 2010). This can run from minutes to hours. Excursions are likely to be lost because of the averaging that occurs due to mixing in the bag.

Oxygen-measuring instruments containing electrochemical sensors were developed many years ago (Nei, 2007). The original instruments provided a discrete measurement over a period of about 30 seconds. The ability to capture an excursion with any of the preceding measurement technologies depends on timing and duration of sampling. The potential to capture an excursion using the approaches discussed here was small. It was not possible to capture the detail provided in Tables 2 and 3 until recently. The cited approaches were the only ones available for assessing conditions at the time of publication of current guidelines and regulatory limits that incorporate the 19.5% floor exposure limits. This contrasts with the measurement technology and data processing capability of the instruments used in this study. The resolution time is controlled by the data processing capability and is effectively 3 seconds or less versus 30 seconds or longer for older technologies. The ability to capture the full impact of excursions from the baseline depends only on the duration of the sample period within the work shift and not happenstance during the sequencing of measurement.

Given the relativity of context provided by discussion of the limitations of historic versus current measurement technique, interpretation of the data obtained here can occur from two perspectives. The first reflects the literal and absolute interpretation of the minimum (or floor) that a single, almost instantaneous excursion at or below the regulatory floor (19.5%) measured during a day-long sample dictates a response consistent with an oxygen-deficient condition. This would require use of NIOSH-approved respirators whenever welding in oxygen-deficient conditions and, therefore, would require replacement of all other forms of respiratory protection.

In the U.S., OSHA (1998) offers a small concession, allowing use of all atmosphere-supplying respirators down to oxygen levels of 16% subject to altitude. This approach still does not address the question about the absolute nature of this interpretation and risks imposed by requirements to wear atmosphere-supplying respirators full time. It also raises the question of whether resources expended to obtain and service these respirators could be better used to provide better protection to the welders who are required to wear them.

The second perspective considers the fact that the 19.5% floor is an administrative limit that contains a safety factor acknowledged by NIOSH and that some level of flexibility should exist where excursions are small and very short in duration relative to the length of the work shift (NIOSH, 1976, 2005). This perspective reflects previous discussion about the acceptance of lower oxygen levels in regulatory limits (as low as 16%) in previous times when measurement techniques were considerably less precise (McManus, 1999).

The difficulty with this concept is that without regulation or other guidance, it is completely open to interpretation with obvious consequences. The question that this approach raises is whether the welders require extra protection in view of the excursions identified in this study where continuous mechanical ventilation is also occurring as part of a regulatory requirement. The key to resolving this situation is to eliminate or mitigate the excursions in oxygen concentration. The means for doing this is effective ventilation of the work spaces. Effective ventilation means use of the local exhaust system to capture the plume and use of air movers in a coordinated manner to provide supply ventilation (Figure 1).

The more global perspective highlighted by this study is that depression of oxygen to any level below 20.9% is functionally legal only in narrow circumstances during normally encountered types of work. These include atmospheres enriched in nitrogen; atmospheres containing high levels of water vapor, mist or steam; and atmospheres containing chemically inert gases (in practical terms, helium and argon). The implication behind this statement is that any depression of the oxygen level demands investigation to determine the cause and action reflective of the respective regulatory limit or guideline. This reality exposes the bigger question about the best setting for the oxygen alarm prior to obtaining a reading in an atmosphere containing otherwise undetectable contamination.

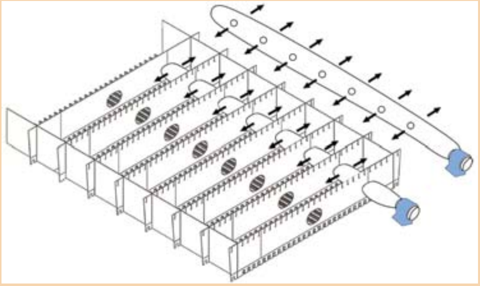
The concern is that the depressed reading on the oxygen sensor could be the only indication of the abnormal condition. That is, the depressed reading indicates the presence of another chemical substance at a level that could pose serious concern. Identification and quantification of that substance are paramount to ensuring the continued safety of workers affected by the reading.

Operation of these instruments in off-on mode rather than ongoing operation could fail to determine the presence of the contamination due to resetting of the oxygen sensor to 20.9% at time of start-up. This reality argues for setting the alarm of the oxygen sensor as close as possible to the ambient value of 20.9%, regardless of the regulatory limit. Experience gained from alteration of the baseline due to weather conditions suggests that an alarm setting of 20.5% for the oxygen sensor will not incur undue false positive alarms under ambient conditions of continuous operation. In industries beyond

Portable fans were used to ventilate large ship structures during welding.

Figure 1

Supply Ventilation System



Supply ventilation system for ventilating confined and enclosed spaces in ship structures.

the shipbuilding environment, the reading of the oxygen sensor during work in confined spaces in which ventilation is occurring is almost always 20.9%. During ship construction, alarms at the upwardly revised set-point indicate lack of control over welding emissions or shield gas leakage.

These observations argue for harnessing normality to indicate abnormality. In most industrial situations, nothing can be gained from using the current regulatory limit of 19.5%. Information provided in this situation by real-time, datalogging instruments containing oxygen sensors is consistent with that obtained in confined spaces in other industrial sectors in which similar monitoring occurs pursuant to regulatory requirements. Datalogging provides the means to identify, analyze and interpret excursions in time, duration and magnitude. The results support use of continuous monitoring instruments to detect situations not anticipated in the work plan because of the absence of warning properties of oxygen-deficient conditions.

Conclusion

These results indicate that the diverse activities of welding of aluminium in the shipbuilding environment, as described in this article, posed a low risk of oxygen deficiency relative to the regulatory limit of 19.5%, and a very low risk of physiological oxygen deficiency relative to maintaining 90% saturation of hemoglobin at a concentration of 14% oxygen at sea level. The results also support routine monitoring for oxygen in this environment given the deliberate loss of containment of argon during welding and the unintended loss due to leakage and other mishaps. **PS**

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