Argon-Related Fatigue

An Investigation in an Aluminum Shipbuilding Environment

By Neil McManus and Assed N. Haddad

Fatigue is a nonspecific condition that affects people periodically in life (CCOHS, 2014; Nordqvist, 2014). People with fatigue often express lack of energy, discomfort, feeling unwell or sleepy, loss of motivation, poor concentration, and difficulty in making decisions and performing daily tasks. Expression of fatigue in individuals and collectively in groups raises obvious concerns about safe performance of work (CCOHS, 2014; Hallowell, 2010). One can cite many causes for fatigue, including recent or current illness; pregnancy and early child care; overconsumption of caffeinated products; stress induced by bereavement; moving to a different home; divorce; work problems; jet lag; depression; boredom; lack of sleep; and medical issues including some types of poisoning, vitamin or mineral deficiency, anemia and thyroid problems. Complicating matters further is the potential role of prescription drugs in fatigue. Statins, which lower cholesterol and are among the most commonly prescribed medications, can cause tiredness and decreased energy upon exertion (Golomb, Evans, Dimsdale, et al., 2012).

Fatigue is not normally a basis for setting exposure guidelines except for lifting and other musculoskeletal concerns (ACGIH, 2001b). Physical fatigue often results from overexertion and excessive repetition of tasks over a long period. Mental fatigue can result from task repetition and long periods of intense concentration (CCOHS, 2014; Hallowell, 2010). Thus, fatigue is an unusual basis for investigating work that is not considered strenuous or repetitive, or does not impose lifting requirements.

An Unusual Case

This investigation was initiated when a group of workers fabricating large welded structures from aluminum at a shipyard in Vancouver, British Columbia, expressed concerns about fatigue. Their concerns had begun during welder training at the on-site school and continued during production; similar concerns were expressed by workers in all of the buildings in which this activity was performed.

These workers worked an 8-hour daytime shift. They reported unusual levels of fatigue and expressed the depth of these concerns in an emphatic manner. Several workers exercised

IN BRIEF

- **This article examines the role argon plays in causing unusual fatigue among workers at ambient conditions. Occupational hygiene has long considered argon to be physiologically inert, yet the diving literature indicates that argon produces effects even at low gas pressure used at shallow depths.**
- **Exposure to argon was estimated from 33,600 minute-by minute measurements of oxygen during gas-shielded welding and related work.**
- **Exposure to argon varied with job title, and by work location and orientation. This study provides a starting point for discussion about setting an occupational exposure limit for argon under ambient conditions.**

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seniority rights and returned to work on steel structures. Some exercised the right to refuse what they perceived to be unsafe work and one individual was excused for medical reasons.

Understanding the nature and cause of these concerns was critical. The cause was not immediately apparent based on a review of chemical use, ergonomic issues and exposure to physical agents. The work was performed indoors in a partly climate-controlled building. Humidity control and cleanliness are important issues in the aluminum shipbuilding environment, so the air is clean compared to that in a steel shipyard where welding smoke (particles of fume created during welding) is readily visible. Work on steel structures also typically occurs outdoors in less-hospitable conditions.

The welding tasks followed industry-standard processes and practices. Thus, investigators started with the premise that every agent present known to affect workers was a potential cause of the symptoms. At the time of this investigation, the literature contained no reference to exposure to argon during welding. Argon and the other inert gases are among the few contaminants permitted in the atmosphere to depress oxygen to the guideline level and regulatory limit (ACGIH, 2001b; OSHA, 1993, 1994).

Identification of an undocumented effect of argon would force reconsideration of current thinking about guidelines and regulatory limits for exposure. Quantization of exposure was the only way to determine occurrence of a possible previously undocumented effect. Accordingly, this research aimed to determine breathing zone exposure to argon by workers engaged in fabricating large ship structures from welding of aluminum. A companion article (McManus & Haddad, 2015) examines the results of monitoring for oxygen levels during tacking, fitting and welding. Estimation of exposure to argon is a by-product of measurement of oxygen.

To understand the nature of the problem on a personal level, the researchers compiled voluntarily provided, confidential anecdotal information regarding symptoms and respirator use. No records were created that would enable participant identification. Participants described the fatigue condition as sleep inducing and said it occurred after work, either during the afternoon commute or later at home. The fatigue condition affected individuals regardless of age, gender, and use of air-purifying or air-supplying respiratory protection.

Participants' comments also indicated that the fatigue condition was work-related. That is, the symptoms disappeared after a prolonged period away from work and reappeared following return to work. Anecdotal information about welding on other metals (stainless and carbon steels) and aluminum in other environments indicated that fatigue was an issue in all workplaces where argon or argon blends were utilized as the shield gas.

A Review of the Welding Process

Welding processes in use during this project included gas metal arc welding [GMAW, also known as metal inert gas (MIG) welding] for tacking, fitting and production welding, and gas tungsten arc welding (GTAW) (also known as tungsten inert gas welding) for touch-up work. Both types of welding use argon and argon blends for shielding (Althouse, Turnquist, Bowditch, et al., 1988).

Welding during this project consumed considerable quantities of argon or a blend containing 25% helium/75% argon (He/Ar). Emission of argon into the building's airspace at ambient temperature occurred from leaks in couplings and valves and during purging of the hoses, feeding wire into the welding gun and pre-arc injection onto the metal surface.

Shield gas flows through the gun whenever the trigger is activated, regardless of whether welding is occurring. Gas flows at 22 L/min (about 1.5 m/s through the opening). This flow rate is needed to establish and maintain the puff of gas formed above the metal prior to and during welding. Shield gas at both ambient temperature and in the hot plume during welding can accumulate in work spaces created by metal structures of the appropriate geometric configuration. Argon or He/Ar provides no warning properties (color, odor, taste or irritation) to the senses.

Welder training occurred in an on-site facility that contains partitioned booths in which a trainee could practice technique to develop skill. Each booth contained a workbench and an overhead, adjustable local exhaust hood for collecting and extracting the welding plume from the building. The researchers did not investigate the effectiveness and use of this system.

The fabrication building had a high-velocity, low-volume exhaust system that contained many inlets to connect hoses and collector hoods. The latter system was nearly impossible to utilize for several reasons, including the welder's inability to see the location of the welding plume for positioning the collector hood because of the dark shade of the lens used for viewing the arc. Positioning the collector hood onto existing surfaces or a holding device was also problematic because the nonferrous nature of aluminum precludes magnetic attachment and because the considerable variety of geometric configurations required many clamping configurations.

In either situation, to effectively collect and remove the hot plume, the welder must position the collector hood above and to the side or front, away from the face. The hot plume contains the shield gas(es) as well as atmospheric gases entrained during collection.

Maintaining the integrity of the gaseous shield around the arc is essential for creating welds that meet requirements for quality. Overly aggressive collection of the plume will destroy the gaseous shield on which weld quality depends. Positioning the hood of the local exhaust equipment in a location that does not destroy the shield through induced turbulent motion is an acquired skill that requires intuition and attention to detail.

During welding, the worker's face is close to the flow of shield gas. This is true whether the welding process is manual or automated using a portable welding machine. In this case, the portable welding machine was self-propelled and was used on the shop floor to weld together large plates of aluminum. In both cases, the welder positions his/her face close to the arc in order to observe the progress and quality of the weld, and to track the machine along the seam to be joined. This close proximity to the arc subjects the welder to exposure to the shield gas.

Welding occurs downward onto lower horizontal surfaces; upward, downward and side-to-side on vertical surfaces; and upward onto horizontal overhead surfaces. During welding downward onto lower horizontal surfaces in the absence of effective local exhaust ventilation, 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 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 the welder's face to be immersed into the plume.

Argon in Welding

A cloud of pure argon at room temperature is about 1.4 times as dense as a cloud of air at the same temperature (Haynes, 2001). As a result, a cloud of pure argon tends to settle to the lowest level in a structure or remains in that location when generated there. At high temperature in the welding plume, argon rises to the highest level in the structure's/building's airspace consistent with buoyant forces. The latter is readily observable. Accumulation of argon in workspace air is distinctly possible in the absence or inefficient use of supply and/or exhaust ventilation systems.

Literature Review

Argon is chemically inert and is considered physiologically inert in the industrial hygiene literature. The only notable concern with argon is oxygen deficiency caused by displacement or dilution of the atmosphere. For this reason, argon and other gases that behave in a similar way are known as simple asphyxiates. At this time, no guidelines exist for exposure to the chemically inert gases and argon, in particular based on toxicological effects. Exposure to argon is addressed solely through depression of oxygen (ACGIH, 2014).

However, in the diving literature involving pressurized gases argon is cited as a narcotic and an anesthetic (Bennett, 2003). Diving gases include synthetic mixtures of gases formulated to minimize risk to divers of developing narcosis (severely compromised judgment). In deep diving, preventing narcosis is vital. Argon narcosis is about 2.3 times as severe as nitrogen narcosis. Helium narcosis is only about 0.25 times as severe as nitrogen narcosis. This is the major reason that helium is used in, and argon is excluded from, gas mixtures used in diving (Brunton, Chabner & Knollmann, 2010). Concern about argon narcosis typically extends to depths greater than 30 m (Unsworth, 1966). However, historic references cited by Unsworth (1966) indicate concern at depths considerably less than 30 m.

More recently, Petrie (2003) reports on testing 15 experienced male divers in a chamber at 1 bar (normal atmospheric pressure), and 2, 3 and 4 bars over 5 consecutive days using a battery of computer-generated psychological tests. Total test solving time, minimal single task solving time, total "ballast" time and total number of errors were recorded. Petrie (2003) notes that depths from 10 to 30 m usually are not considered narcotic in scuba air diving. In addition, evidence in the literature of psychomotor disturbances attributable to nitrogen narcosis at these depths is weak and contradictory. Despite this, effects reflective of nitrogen narcosis were evident at all hyperbaric pressures along with marked differences in performance between subjects. These results suggest that nitrogen narcosis in shallow air diving (10 to 30 m) might be a problem in underwater operations that require accuracy, speed, limited time of performance and complex psychomotor processing.

Narcotic and anesthetic effects involve the brain and nervous system (Andrews & Snyder, 1991). Such effects are the common acute outcome from inhalation of almost all solvents, regardless of composition. This is believed to occur because these molecules can migrate from the blood into the fatty tissue. Many molecules found in organic solvents are nonpolar. This means that there is no net electrical charge at any point on the molecule's surface. Inert gases are present as unattached atoms, not molecules, and similarly are non-polar. It seems reasonable to expect that inert gas atoms will behave similarly to nonpolar molecules of the same size and weight (Drummond, 1993).

The nervous system contains a high proportion of fatty material, which is a major component of the insulation that surrounds nerve cells and their surface. This insulation allows electrical signals to pass along the surface of the nerve cell. Organic molecules found in solvents are believed to exert their effects on these structures (Andrews & Snyder, 1991).

Welding processes employed during aluminum shipbuilding are sources of exposure to gaseous and particulate air contaminants (NIOSH, 1988). Principal among the gaseous hazards are ozone (O_3), nitric oxide (NO), nitrogen dioxide (NO_2), argon and possibly dioxide (CO_2), the latter reflecting presence in a blend of shield gas. None of these contaminants is described in the literature as causing fatigue (ACGIH, 2001b; NIOSH, 1988). Aluminum grinding and milling also occurred during this work. Grinding is the source of finely divided particles of airborne metallic aluminum. Finely divided particles of metallic aluminum are potentially chemically reactive. Milling produces metal chips that are too large to become airborne.

Argon is used in various industrial applications (Royal Society of Chemistry, 2015). These include provision of an inert atmosphere in process situations such as production of titanium and other reactive elements; inerting in incandescent and fluorescent lamps; and shielding to exclude oxygen during welding. More exotic uses include filling the gap between panes of glass in double- and triple-glazed windows; and pressurizing tires of luxury cars to protect the rubber against oxidation and to reduce road noise. Such applications indicate that the potential for exposure to argon at levels beyond those present in the ambient atmosphere is possible and that symptoms of fatigue reported in this shipyard may be occurring in other areas of industry. Welding is an open system involving deliberate semicontrolled release of argon into the environment. Other applications involve closed systems.

Study Materials & Methods

Argon in air is difficult to measure accurately, especially in an active workplace environment. In fact, there is no standard method for measuring argon in workplace air. To illustrate, ACGIH (2001a) does not list any equipment for measuring argon or inert gases. Similarly, NIOSH's manual of analytical methods (2003) does not list any methods related to measuring argon or inert gases. Measuring argon in air would require collection of an air sample in a suitable container followed by laboratory analysis. This approach is impractical for assessing conditions in the normal context of the workplace and, in particular, the welding environment.

An alternative to direct measurement of argon is to measure the oxygen level, then back calculate from depression of the baseline. The normal level of oxygen in the atmosphere is 20.9%. In the absence of displacement or dilution caused by the presence of another substance, the expected cause of decrease in oxygen level would be due solely to argon at levels beyond the ambient concentration in the atmosphere.

Equation 1 provides the quantitative relationship between the concentration of oxygen measured by the instrument and the concentration of argon that depressed the reading from the baseline level.

$$\text{Concentration of argon} = (\text{baseline} - \text{oxygen reading})\left(\frac{100}{20.9}\right)$$

The baseline is the concentration of oxygen reported by the instrument in air uncontaminated by argon at the same time. Oxygen reading is the reading in air containing argon contamination. The fraction (100/20.9) corrects for the fact that the oxygen sensor measures one molecule out of every five in the atmosphere that enters the sensor by diffusion. This relationship is applicable to estimating the concentration of argon in air.

Two standard handheld portable instruments containing an oxygen sensor and a datalogger (MicroMax, Lumidor Safety Products, Miramar, FL) were used to measure oxygen levels. This type of instrument is routinely used for assessing conditions in confined spaces. The instruments were secured in the upper pocket of the welder's coveralls and the sampling probe onto the top of the shoulder. The instruments contain a built-in pump and probe for remote sampling. The manufacturer specifies repeatability of ±2% for the sensors and accuracy of 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.

The instruments were started in an office remote from the fabrication building at the beginning of the shift (around 7:00 a.m.) to establish the benchmark concentration for oxygen (20.9%) and the zero point for the other sensors in an atmosphere known to contain no argon beyond the ambient level in the atmosphere and no other contamination.

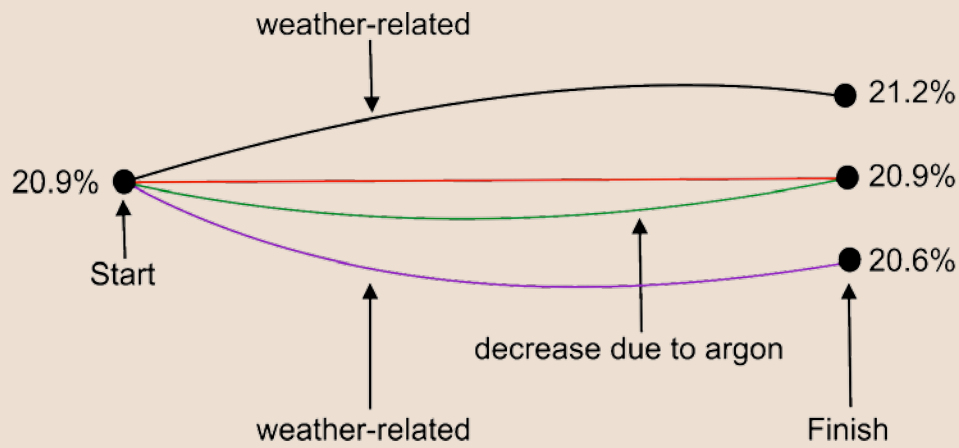
Of the two types of oxygen sensors available, the instruments contained partial-pressure sensors. Partial-pressure oxygen sensors have a relatively large opening into the interior that is covered by a diffusion barrier (City Technology, 2014). This opening allows diffusion of gases from the atmosphere. The sensor is sensitive to changes in barometric pressure and altitude. The partial pressure of water vapor is about 10 Torr (1 Torr = 1 mm_{Hg}) at normally encountered temperatures. This also reflects moisture content in the air, especially when rain is falling and later when drying occurs. 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 location of the shipyard, is about 760 Torr (Moran & Morgan, 1989). Therefore, equipment start-up occurred in an environment that contained a level of oxygen subject to slight variations in partial pressure and interpreted within tolerances contained in the programming of the software in the instrument as 20.9%. All readings obtained during the day were subject to variations reflective of changes in barometric pressure relative to the condition at time of start-up.

The datalogging circuit in the instruments samples the signal from the oxygen sensor every 3 seconds and temporarily stores the highest or lowest value relative to 20.9% in memory. At the end of each 1-minute interval, the circuit transfers this value for retention into the datalogger. One minute is the smallest value of the sampling interval; 5 minutes is the longest value. A warning alarm sounds when the oxygen level decreases to 19.5% or less.

WorkSafeBC, the regulator in British Columbia, Canada, where the shipyard is located, requires employers to assess work conditions. This assessment required cooperation and active participation from welders and other workers. Everyone who participated was a volunteer and gave informed consent. Prior to beginning, each prospective participant received a brief explanation about what the instrument did and the information it creates and stores. Anyone uncomfortable with participation was excused, no questions asked, and without repercussion. No names were recorded to ensure anonymity.

Figure 1
Variation of Oxygen Levels During Near-Shift-Length Samples



Study Results

Datalogger output provided the minimum minute-by-minute level of oxygen below 20.9% and the maximum value above 20.9% from the instrument. On most days, the baseline remained at 20.9% all day (Figure 1). On some days, the baseline decreased during the day and returned to the starting level of 20.9% at the end of the day when exposed to air known not to contain argon beyond the ambient level. The decrease in oxygen level on these occasions was interpreted as being due to argon because of restoration of the baseline to 20.9% in air known not to contain argon beyond the ambient level.

On some days, the baseline decreased or increased gradually and remained at the new level throughout the day, including during exposure to air known not to contain argon beyond the ambient level. The baseline decreased to as low as 20.6% and increased to as high as 21.5%. The cause of the shift in the baseline was attributed to an agent other than argon. The change appeared to reflect the passage of weather systems, namely rain in the morning and sun in the afternoon and vice versa.

The presence of argon in the atmosphere during welding also caused transients characterized by sudden decrease in the level of oxygen followed by equally rapid recovery to the baseline level. Generally these changes were small and the level returned quickly to the baseline (McManus & Haddad, 2015). Maximum total duration of the transient was two measurement intervals, or 2 minutes. Given the manner in which the datalogger operated, the actual duration of the depression and recovery of the oxygen level could have required considerably less time.

Exposure to argon was estimated by adding the depression from 20.9% where known to be due to argon, to the new baseline and the transients from the baseline, and dividing by the total duration of the sample (Equation 2).

$$\text{Average concentration} = \left(\sum \frac{\text{(baseline} - \text{oxygen reading)(excusion duration)}}{\text{total sample duration}}\right)\left(\frac{100}{20.9}\right)$$

The sum of the decreased level of oxygen in the depressed baseline and the transients effectively provides an integrated exposure measured in % x min. This calculation assumes constant exposure at that level for one minute. This is reasonably true for depression of the baseline from 20.9% over a long period attributable to argon where the baseline is constant but not strictly true in the case of transients in which rapid change occurs. This is the case in the latter situation because the instrument saves only the lowest value during the sampling interval. This situation introduces a likely source of overestimation error for transients.

Adding the excursion and transient products and dividing by the total number of minutes during which the device operated (% x min)/(min) provides the average concentration of argon in the exposure in percentage. The fraction (100/20.9) corrects for the fact that the oxygen sensor measures one molecule out of every five in the atmosphere that diffuse into the sensor.

Tables 1, 2 and 3 (pp. 52-54) summarize results from sampling for argon. These samples comprise a total of 33,600 minute-by-minute measurements of oxygen during welding and related work in different geometric configurations over a prolonged period. Welding occurring during this work was argon-shielded GMAW (or MIG) welding (Althouse, et al., 1988).

Tasks listed in Tables 1, 2 and 3 are based on job classification, type of work and the potential for atmospheric confinement by type of structure. This provides a basis for estimating exposures across the spectrum of structures. While structures have different shapes, the fundamental geometric configurations in which work occurs remain the same.

In this shipyard, the most pronounced exposures to argon occurred during overhead welding in the engine bed where the upper surface trapped the plume. Episodes of lesser magnitude occurred during work downward on horizontal surfaces at the bottom of frames and in the highly enclosed compartments in the center module. There is some indication that these excursions reflect individual work styles. Different people performing the same task in the same location at the same time experienced considerably different conditions. Many transients contained only one or two values below the baseline meaning that these episodes lasted at most 2 minutes.

Table 4 (p. 55) provides summary statistics including the geometric mean and geometric standard deviation. The geometric mean provides a basis for comparing different types of monitoring situations and tasks. The geometric mean is the antilog of the arithmetic average of the natural logarithms of the individual values. Industrial hygiene data are found to follow the lognormal statistical distribution (Leidel, Busch & Lynch, 1977). That is, when plotted, the curve formed from the probability of occurrence of the measured values is displaced to the right (high concentrations) with a long tail. This model is believed to provide the best estimate of central tendency of the individual measurements collected during industrial hygiene sampling. Indeed, that was the case in this situation as reported by Industrial Hygiene Data Analyst, Lite Edition with the exception of samples obtained during work in the engine bed under confined conditions.

Geometric mean argon exposure varied according to type of work. Exposure generally increased as proximity to the welding arc increased. That is, exposures increased in the following sequence: laborers and ventilation providers < tackers and fitters < production welders. This finding is consistent with the expectation that exposure reflects proximity to source. However, it does not provide the basis for establishing a dose-response relationship (a standard relationship in toxicology) based on job classification, orientation of welding and extent of geometric confinement.

Geometric mean exposures of the clean-up laborer and ventilation provider ranged from 0.043% to 0.045%. This suggests that a consistent background level of argon is measurable in the building at normal working height. This reflects release into the airspace from numerous sources. The large doors at the ends of the building normally remained closed. Natural flow as a means of ventilating the structure with outdoor air was strongly discouraged because of the need to maintain the constant temperatures necessary for work with large quantities and surfaces of aluminum.

Geometric mean exposures of fitters ranged from 0.11% to 0.30% and tackers, from 0.12% to 0.15%. Fitters and tackers usually work together; thus, similar exposure is expected in these occupations. Geometric mean exposures of production welders ranged from 0.45% to 0.87%. Within the group of production welders, geometric mean exposure during work with automated welding machines was 0.43%; during work with plumes unconfined by structures ranged from 0.44% to 0.81%; and during work with plumes confined

Table 1

Exposure to Argon During Support Work, Fitting & Tacking

Location/description	Duration (minutes)	Integrated difference (% x minutes)	Average difference (%)	Exposure concentration (%)
Tasks unrelated to welding				
Cleanup laborer, working throughout the building	445	86.8	0.20	0.96
	385	6.2	0.016	0.077
	446	1.1	0.0025	0.012
	444	4.9	0.011	0.053
	393	0.3	0.00076	0.004
Ventilation provider, worked throughout the building	377	0.6	0.0016	0.0077
	441	2.3	0.0052	0.025
	440	9.8	0.022	0.11
	376	7.9	0.021	0.10
	433	6.5	0.015	0.072
Fitting				
Fitting frames in open area of the building	451	36.5	0.081	0.39
	397	1.6	0.0040	0.019
	389	16.4	0.042	0.20
Fitting frames in engine bed, open at top	418	115.5	0.28	1.3
	427	5.8	0.014	0.07
	416	14.9	0.036	0.17
	424	65.1	0.15	0.72
	395	30.9	0.078	0.37
	409	32.8	0.080	0.38
	428	12.0	0.028	0.13
Tacking				
Tacking downward on horizontal surfaces of frames in open area of building	219	48.1	0.22	1.1
	124	0.4	0.0032	0.015
	220	8.9	0.040	0.19
Tacking on vertical surfaces of frames in engine bed, open at top	375	3.1	0.0083	0.040
	397	11.1	0.028	0.13
	411	28.3	0.069	0.33
	376	8.2	0.023	0.11
	412	9.4	0.023	0.11

by structures, from 0.51% to 0.87%. Confinement of the plume in structures increased geometric mean exposures slightly.

Within each group, the geometric configuration in which the work occurs can produce differences in exposure. To illustrate, the exposure of fitters exceeded that of tackers during work in the engine bed, whereas exposure during tacking was consistent regardless of the geometric configuration.

Geometric standard deviation (GSD) is a measure of the variability of readings in a group (Leidel, et al., 1977). Smaller values indicate tighter fit to the lognormal distribution. GSD values ranged from 1.32 to 8.67. The smallest values imply that the most consistent exposures occurred during production welding. Clean-up, provision of ventilation, and tacking and fitting experienced considerably higher GSDs. Increased GSD during these activities is explainable by the considerably greater variability in these tasks.

The work involved about 20 production welders, 5 tackers and 5 fitters, 1 laborer who managed portable ventilation equipment and 2 supervisors. Participation varied considerably from one session to multiple sessions depending on comfort in wearing the sampling equipment, interest in the project and the type of work that was occurring. Monitoring attempted to obtain samples from all relevant types of activity. Sampling was spread among the group of workers over a nearly 2-month sample period.

Sampling was dictated in part by availability of work in specific structures and different geometric configurations as indicated in the tables in the results. In the case of automated welding using the A2 and Bug machines, the operator wore the sampling device. The realities intrinsic to this situation introduced considerable randomness into the sampling because the work schedule was not known in advance of seeking volunteers for a particular day. Another factor was the need to obtain as many samples as possible within the limited time available with only two instruments and a dynamic schedule. To the extent possible, the researchers attempted to maximize randomness and to minimize bias.

Discussion

In the absence of a regulatory exposure limit for argon, no direct significance regarding compliance can be put on the results presented here. Their value lies in establishing exposures during this work and creating a body of knowledge about the potential role of argon in the unusual and overwhelming fatigue experienced by workers engaged in this project and possibly other work involving argon-shielded welding. Exclusion of other agents following review of the literature and extensive personal sampling as necessary would mean that argon must receive careful consideration as the cause.

Some of the work occurred in workspaces that meet generally accepted criteria for classification as confined spaces in British Columbia and in other jurisdictions (OSHA, 1993, 1994; WorkSafeBC, 2014). Historic research establishes the role of oxygen deficiency as a causative agent in fatal incidents that occur in these work spaces (NIOSH, 1979, 1994; OSHA, 1985). Extensive review of incidents from numerous sources provides insight into development of the atmospheric hazard, namely existence prior to entry versus development during work activity (McManus, 1999; McManus & Haddad, 2014).

Use of argon and other shield gases in welding processes is a work activity that carries risk of development of oxygen-deficient conditions. That is, atmospheres that become enriched in argon become deficient in oxygen. This concern parallels the occurrence of fatigue reported by these workers. Study results show that the average concentrations of argon measured in this investigation and associated with worker fatigue were considerably less than those needed to depress the concentration of oxygen below the regulatory limit for oxygen deficiency of 19.5% (Bollinger, 2005; OSHA, 1993, 1994; WorkSafeBC, 2014).

Table 2

Exposure to Argon During Automated & Manual Production Welding, Unconfined Plume

Location/description	Duration (minutes)	Integrated difference (% x minutes)	Average difference (%)	Exposure concentration (%)
Production welding—welding machine				
Automated welder—Bug—production welding (downward) on T-bars in the open building	398	22.5	0.057	0.27
	424	45.7	0.11	0.53
	415	42.1	0.10	0.48
	408	45.6	0.11	0.53
	425	37.4	0.088	0.42
Production welding—manual—unconfined plume				
Production welding downward on frames (horizontal surfaces) in the open building	365	56	0.15	0.72
	357	31.2	0.087	0.42
	392	16.4	0.042	0.20
	413	53	0.13	0.61
Production welding on vertical surfaces in large frames in ring structure	228	38.9	0.17	0.81
	370	63.3	0.17	0.82
Production welding on vertical surfaces in frames in engine bed, open at top	358	23	0.064	0.31
	194	7.9	0.041	0.20
	392	28.1	0.072	0.34
	411	57.7	0.14	0.67
Production welding on overhead and vertical surfaces in jet-tube	191	16.9	0.088	0.42
	379	18.4	0.049	0.23
	441	51.8	0.12	0.57
	222	33	0.15	0.71

The circumstances that prompted this study were unusual and unexpected based on conventional wisdom. This study was performed in response to worker concerns about extreme fatigue experienced at the end of the workday or in early evening related to exposure at work to argon during gas-shielded welding on aluminum. Given argon use in other industrial applications, occurrence of fatigue symptoms, especially in other open systems of exposure, should prompt investigation to determine the full extent of this problem.

Conclusion

This work shows that argon is measurable in the airspace of buildings in which large-scale aluminum structures are being fabricated using gas-shielded arc welding. A gradation in worker exposure to argon is demonstrable by occupation (laborers and ventilation providers < tackers and fitters < production welders) and activity. The greatest exposure occurred during overhead production welding where horizontal surfaces trapped the plume. Individual work style also appears to influence exposure. The noted variation in exposure by occupation and activity forms a potential basis for establishing a dose-response for fatigue produced by exposure to argon in occupational settings.

This study serves to remind OSH professionals, occupational health physicians and industrial hygienists about the need to respond when people express concern about the conditions of work despite the seeming familiarity of the territory. This study shows consistency with measurable neurological effects reported in the diving literature during shallow dives using mixtures containing nitrogen, a more potent narcotic and anesthetic agent than argon. The occurrence of narcotic and anesthetic effects in workers exposed to argon during gas-shielded arc welding is plausible. **PS**

Table 3

Exposure to Argon During Manual Production Welding, Confined Plume

Location/description	Duration (minutes)	Integrated difference (% x minutes)	Average difference (%)	Exposure concentration (%)
Production welding—manual—confined plume				
Engine bed, overhead welding inside space formed by engine girders and bottom sheet	466	24.2	0.052	0.25
	217	105.2	0.48	2.3
	80	5.9	0.074	0.35
	379	38.8	0.10	0.48
	280	17.9	0.064	0.31
	392	68.6	0.18	0.86
	397	2.3	0.0058	0.028
	383	39.2	0.10	0.48
	363	65.7	0.18	0.86
	356	88.5	0.25	1.2
	174	20.8	0.12	0.57
	403	44	0.11	0.53
	407	95.9	0.24	1.1
	216	44.4	0.21	1.0
	331	47.3	0.14	0.67
	359	189.4	0.53	2.5
	352	74	0.21	1.0
	393	62.6	0.16	0.77
	399	36	0.090	0.43
	402	33.9	0.084	0.40
	382	154.5	0.40	1.9
	278	41.6	0.15	0.72
	378	104.5	0.28	1.3
	398	65.4	0.16	0.77
Production welding on vertical surfaces in completely enclosed compartments of 400 series structures (wet deck)	135	23.3	0.17	0.81
	412	24.3	0.059	0.28
	169	29.5	0.17	0.81
	370	28.3	0.076	0.36
	376	79.3	0.21	1.0
	104	4.5	0.043	0.21
	440	48.4	0.11	0.53
	157	5.6	0.036	0.17
	144	26.4	0.18	0.88
Production welding on vertical surfaces in completely enclosed compartments of 200 series structure (bow)	182	83.1	0.46	2.2
	228	35	0.15	0.72
	382	58.1	0.15	0.72
	450	47.1	0.10	0.48
	420	110.2	0.26	1.2
	421	59.9	0.14	0.68

References

American Conference of Governmental Industrial Hygienists (ACGIH). (2001a). *Air sampling instruments for evaluation of atmospheric contaminants* (9th ed.). Cincinnati, OH: Author.

ACGIH. (2001b). *Documentation of the TLVs and BEIs.* Cincinnati, OH: Author.

ACGIH. (2014). *Threshold limit values for chemical substances and physical agents and biological exposure indices.* Cincinnati, OH: Author.

Althouse, A.D., Turnquist, C.H., Bowditch, W.A., et al. (1988). *Modern welding.* South Holland, IL: Goodheart-Willock Co. Inc.

Andrews, L.S. & Snyder, R. (1991). Toxic effects of solvents and vapors. In M.O. Amdur, J. Doull & C.D. Klaassen (Eds.), *Casarett and Doull's toxicology: The basic science of poisons* (4th ed.). New York, NY: Pergamon Press Inc.

Bennett, P.B. (2003). Inert gas narcosis. In A.D. Brubakk & T. Neuman (Eds.), *Bennett and Elliott's physiology and medicine of diving* (5th ed.). Philadelphia, PA: W.B. Saunders Co. Ltd.

Bollinger, N. (2005). *NIOSH respirator selection logic* (NIOSH Publication No. 05-100). Cincinnati, OH: NIOSH.

Table 4

Summary Statistics for Argon Exposure

Location/description	Geometric mean concentration (%)	Geometric SD
Tasks unrelated to welding		
Cleanup laborer, worked throughout the building	0.045	7.99
Ventilation provider, worked throughout the building	0.043	3.10
Fitting		
Fitting frames in open area of the building	0.11	4.89
Fitting frames in engine bed, open at top	0.30	2.75
Tacking		
Downward on horizontal surface of frames in open area in the building	0.15	8.67
Vertical surfaces of frames in the engine bed, open at top	0.12	2.12
Production welding—welding machine		
Automated welder—Bug—production welding (downward) on T-bars in open shop	0.43	1.32
Production welding—manual—unconfined plume		
Downward on frames (horizontal surfaces) in open shop	0.44	1.77
Downward on bottom surfaces of large frames in ring structure	0.63	1.46
Vertical surfaces in large frames in ring structure	0.81	---
Vertical surfaces in frames in engine bed, open at top	0.46	1.61
Overhead and vertical surfaces in jet-tube	0.52	1.49
Production welding—manual—confined plume		
Engine bed, overhead welding inside space formed by engine girders and bottom sheet	0.65	2.46
Production welding on vertical surfaces in completely enclosed compartments of 400 series structures (wet deck)	0.51	1.78
Production welding on vertical surfaces in completely enclosed compartments of 200 series structure (bow)	0.87	1.71

Brunton, L.L., Chabner, B.A. & Knollmann, B.C. (Eds.) (2010). *Goodman and Gilman's pharmacological basis of therapeutics* (12th ed.). New York, NY: McGraw-Hill Professional.

CCOHS. (2014). Fatigue (OSH answers). Retrieved from www.ccohs.ca/oshanswers/psychosocial/fatigue.html

City Technology. (2014). Oxygen sensors. Retrieved from www.citytech.com/index.html

Drummond, I. (1993). Light hydrocarbon gases: A narcotic, asphyxiant or flammable hazard? *Applied Occupational and Environmental Hygiene, 8,* 120-125.

Golomb, B.A., Evans, M.A., Dimsdale, J.E., et al. (2012). Effects of statins on energy and fatigue with exertion: Results from a randomized controlled trial. *Archives of Internal Medicine, 172,* 1180-1182.

Hallowell, M.R. (2010, Dec.). Worker fatigue: Managing concerns in rapid renewal highway construction projects. *Professional Safety, 55*(12), 18-26.

Haynes, W.M. (Ed.). (2001). *CRC handbook of chemistry and physics* (92nd ed.). Boca Raton, FL: CRC Press.

Leidel, N.A., Busch, K.A. & Lynch, J.R. (1977). *Occupational exposure sampling strategy manual* (NIOSH Publication No. 77-173). Cincinnati, OH: NIOSH.

McManus, N. (1999). *Safety and health in confined spaces.* Boca Raton, FL: Lewis Publishers/CRC Press.

McManus, N. & Haddad, A.N. (2014, Oct.). Confined space incident reconstruction: The future depends on understanding the past. *Professional Safety, 59*(10), 51-59.

McManus, N. & Haddad, A.N. (2015, Aug.). Assessment of oxygen levels during welding in an aluminum shipbuilding environment. *Professional Safety, 60*(8), 26-32.

Moran, J.M. & Morgan, M.D. (1989). *Meteorology: The atmosphere and the science of weather* (2nd ed.). New York, NY: Macmillan Publishing Co.

NIOSH. (1979). *Criteria for a recommended standard: Working in confined spaces* (NIOSH Publication No. 80-106). Cincinnati, OH: Author.

NIOSH. (1988). *Criteria for a recommended standard: Welding, brazing and thermal cutting* (NIOSH Publication No. 88-110). Cincinnati, OH: Author.

NIOSH. (1994). *Worker deaths in confined spaces* (NIOSH Publication No. 94-103). Cincinnati, OH: Author.

NIOSH. (2003). *NIOSH manual of analytical methods* (4th ed., 3rd suppl.) Cincinnati, OH: Author.

Nordqvist, C. (2014). What is tiredness or fatigue? How can I beat tiredness? *Medical News Today.* Retrieved from www.medicalnewstoday.com/articles/8877.php

OSHA. (1985). Selected occupational fatalities related to toxic and asphyxiating atmospheres in confined work spaces as found in reports of OSHA fatality/catastrophe investigations. Washington, DC: Author.

OSHA. (1993, Jan. 14). Permit-required confined spaces for general industry: Final rule. *Federal Register, 58*(9), 4462-4563.

OSHA. (1994, July 25). Confined and enclosed spaces and other dangerous atmospheres in shipyard employment: Final rule. *Federal Register, 59*(141), 37816-37863.

Petrie, N.M. (2003). Change in strategy of solving psychological tests: Evidence of nitrogen narcosis in shallow air diving. *Undersea Hyperbaric Medicine, 30*(4), 293-303.

Royal Society of Chemistry. (2015). Argon. Retrieved from www.rsc.org/periodic-table/element/18/argon

Unsworth, I.P. (1966). Inert gas narcosis: An introduction. *Postgraduate Medical Journal, 42,* 378-385.

WorksafeBC. Confined spaces (OHS Regulation, Part 9). Retrieved from www2.worksafebc.com/publications/ohsregulation/regulation.asp

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