Assessment of Technologies for Measuring Exposure to NO$_2$ during Welding on Aluminum Alloys

Thomas Neil McManus[1, 2] & Assed Haddad[3]

[1] NorthWest Occupational Health & Safety, North Vancouver, Canada

[2] Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

[3] Escola Politécnica, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Correspondence: Thomas Neil McManus, North West Occupational Health & Safety, North Vancouver, BC, V7K1P3, Canada. Tel: 604-980-8512. E-mail: nwohs@mdi.ca

Abstract

Arc welding is a complex process that results in many air contaminants of health significance to humans. As a result, regulators worldwide require employers to determine exposure of welders and other workers to these contaminants. The very small Exposure Limit for NO$_2$ limits the technology available for assessing exposure. Bias caused by ozone, a known interferent in the measurement of NO$_2$, is a major concern. This investigation involved side-by-side comparison of results provided by handheld instruments containing electrochemical sensors for NO$_2$ to those produced by an air pollution analyzer specific to NO$_2$ using bag samples of plumes collected during production welding (Gas Shielded Metal Arc Welding [GMAW] commonly known as Metal Inert Gas [MIG welding]) on aluminum alloys. The shield gas was argon. Monitoring to confirm utility of the method was performed on welders. Results from all instruments were similar despite differences in measurement technology and instrument and sensor manufacturer. Levels experienced during confirmatory testing on welders to determine exposures of short duration and long intermittency as occur during real-world activity were comparable to the Threshold Limit Value for NO$_2$ of 0.2ppm (parts per million) expressed as a Time-Weighted Average over 8 hours, and were less than the Ceiling Limit of 1ppm used by some jurisdictions. Hand-held instruments containing electrochemical sensors for NO$_2$ and datalogging capability are suitable for use in this application. The ability to draw the sample to the instrument by a pump is an important consideration in providing welder safety and protecting the instrument.

Keywords: Aluminum Alloys, Arc Welding, Argon, Nitrogen Dioxide, NO$_2$, Portable Monitoring Instruments

1. Introduction

1.1 Arc Welding and Workplace Regulatory Requirements

Gas-shielded arc welding is a major process for joining aluminum alloys in shipbuilding operations (Althouse et al., 1988). Principal technologies include Gas Metal Arc Welding (GMAW) also known as Metal Inert Gas (MIG) welding and Gas Tungsten Arc Welding (GTAW) also known as Tungsten Inert Gas (TIG) welding. GMAW (MIG) was used for production welding and GTAW for touch-up work in this operation. Both types rely on a gaseous shield that forms a hemispherical atmosphere surrounding the arc. The gas shield intentionally excludes atmospheric oxygen in order to prevent rapid oxidation of the metal due to the heat and molten state.

The plume rising from the arc contains gaseous and particulate emissions. Gaseous emissions include the shield gases (argon, helium, carbon dioxide, and nitric oxide present in some mixtures) and gases resulting from chemical reactions occurring inside and outside the shield because of the heat (Moyer, 2002; NIOSH, 1988). Nitric oxide (NO) results from reaction between nitrogen and oxygen on hot metal surfaces in the industrial environment and the weld area in particular (Perkins, 1974; Seinfeld & Pandis, 1998). Nitrogen dioxide (NO$_2$) results from subsequent reaction between NO and atmospheric oxygen or ozone (O$_3$). Ozone results from the interaction between Ultra-Violet (UV) energy emitted by the arc and oxygen in the air (McKinlay, 1992).

Gas-shielded arc welding and cutting produce a number of recognized airborne contaminants that can pose health hazards (NIOSH, 1988). Principal among the gaseous hazards are ozone, NO, NO$_2$, inert shield gases argon (Ar) and helium (He), and possibly carbon dioxide (CO$_2$). Prevention of disease and impairment from

exposure to hazardous chemical substances is the function of Regulatory Exposure Limits. Many regulatory authorities have adopted the Threshold Limit Values (TLVs) published by the American Conference of Governmental Industrial Hygienists (ACGIH) as enforceable Exposure Limits (ACGIH, 2018). The current TLVs for NO and NO_2 are 25ppm and 0.2ppm, respectively. The TLVs listed here apply to exposures averaged over 8 hours. Some jurisdictions use a Ceiling Limit for NO_2 of 1ppm (WorkSafeBC, 2018).

Workplace regulatory authorities require employers to assess exposure of workers through air sampling to ascertain the level of these contaminants and to implement control measures to prevent exceedance. This article is one of a series on assessment of exposure to contaminants during argon-shielded welding on aluminum alloys Other articles reported on emission of UV and blue light in the visible region of the spectrum (McManus & Haddad, 2013); use of methanol as a coolant during machining of aluminum (McManus & Haddad, 2014); oxygen levels (McManus & Haddad, 2015a); unusual fatigue among welders and the possible role of argon (McManus & Haddad, 2015b); Cr levels (McManus & Haddad, 2016); exposure of welders to ozone (McManus & Haddad, 2018a); and exposure of welders to NO_2 (McManus & Haddad, 2018b).

1.2 Challenges Involved in Measurement of NO_2 during Arc Welding on Aluminum Alloys

Reduction in 2012 of the TLV for NO_2 from 3ppm to 0.2ppm (ACGIH, 2018) focused attention onto the accuracy, freedom from interference and capability to respond to low levels of detection technologies and products. How to measure exposure of welders to NO and NO_2 is fundamental to this discussion. Hence, the first objective of this study was to create a defensible and repeatable process for selecting a technology for measuring worker exposure to NO and NO_2 during arc welding on aluminum alloys. The second objective was to demonstrate use of the technology under actual conditions in order to confirm applicability to broader study of welder exposure.

Assessment of exposure during arc welding in the aluminum shipbuilding environment must address a number of complicating factors and considerations. These reflect the idiosyncrasies of arc welding; the constraints of the environment in which measurement occurs; the ability of the measurement technology to respond rapidly to changing levels of the substance to prevent overestimation due to the action of interfering substances; and the ability of the user interface to present measured values in a manner that responds to regulatory requirements.

The technical literature offers no guidance in this area. Arc welding imposes high-level emissions of short duration at usually infrequent and unpredictable intervals onto a low-level background. The measurement technology must be able to respond rapidly and correctly to both the high level and background within the time periods involved and not to respond to interferences. Exposure during manual arc welding typically develops over the period of seconds and involves an almost instantaneous transition between background and the high level. Detection technology must be able to respond rapidly to this change.

Much of the research about welding was performed in laboratory simulations (NIOSH, 1988) The only situation comparable in real-world activity involves long-duration production welding on long seams performed either manually or through operation of self-propelled welding equipment. These situations are not typical and do not reflect the orientations of welders and the geometric relationship between welders and the structure on which welding typically occurs during fabrication of large ship structures.

Arc welding creates an environment hostile to people and equipment. These realities impose considerable constraint on exposure assessments. Welder safety and protection of the sampling device against damage and destruction are paramount. A critical requirement intrinsic to assessment of exposure is to position the sensitive element of the measuring device in the 'breathing zone' of the worker (Lynch, 1994). The 'breathing zone' is an imaginary sphere having a radius about 0.6m centered in the middle of the head. This sphere encloses the region in space influenced by inhalation and exhalation. The sensitive element of the measuring device in attempting to sample from the breathing zone must be small and not impose a safety risk because of interference with the welding helmet. Correct positioning of the latter is essential to protect the welder against exposure to the arc. Laboratory simulations offer at best only an approximation of what occurs in reality. Positioning of other components of the measuring device should occur in non-involved areas of the body of the welder, for example the around the waist or inside a front or back pocket of the coveralls.

A regulatory framework imposing a Ceiling Limit rather than a time-weighted average further complicates the situation and demands detection technology that can respond rapidly to change in conditions. Ceiling Limits contain requirements phrased in terms such as 'the level not to be exceeded at any time' (ACGIH, 2018; WorkSafeBC, 2018). The outcome from these requirements is to drive selection of measuring technologies having the minimum possible sample collection time, real-time display and datalogging capability. This type of response for practical use is available only from colorimetric detector tubes and instruments containing sensors

specific for NO_2.

Colorimetric detector tubes connect to a sampling pump. The pump can operate remotely from the tube through use of extension tubing. Colorimetric detector tubes are small and unobtrusive even when connected by tubing to the sampling pump. Packing material in the inlet of the tube used to position the reactive layer prevents entry of potentially reactive particulates and often contains chemically reactive material to remove interfering substances such as ozone. Collection of a sample requires seconds to several minutes depending on concentration of NO_2 (Dräger, 2011; Gastec, 2012; Sensidyne, 2005). NO_2 reacts with the reactive chemical material to produce a change in color. The reading obtainable on a colorimetric detector tube is a time-weighted average over the duration of the sample. The lowest reading on scale on the Dräger tube, Nitrogen Dioxide 0.5/c, is 0.5ppm and on Gastec No. 9L Nitrogen Dioxide, 0.5ppm also. During the era of the TLV of 3ppm this technology was quite serviceable. In the era of the TLV of 0.2ppm, this technology is no longer usable. This technology would potentially be suitable only for evaluation of exposure at the Ceiling Limit of 1ppm. In addition, colorimetric reactions are susceptible to error due to cross reaction involving ozone.

Air pollution instruments used to measure NO_2 utilize ozone in the detection process (Thermo Electron, 2004). Thermo Environmental Instruments Inc., Model 42C, NO-NO_2-NO_x Analyzer (Franklin, MA) processes the air sample through a two-part cycle. In the first part, the air sample passes through a circuit that adds ozone. The ozone oxidizes nitric oxide (NO) to NO_2. This reaction emits light energy that is measured and interpreted as the concentration of NO. In the second part of the cycle, the air sample is routed through a circuit containing a catalyst that reduces the NO_2 to NO. Ozone again is added to the sample and the light measured. The difference in amount of light in the two measurements is interpreted as the concentration of NO_2 originally present. Homogeneity of sample throughout the cycle is essential to obtaining valid results.

Hand-held, portable instruments containing an electrochemical sensor specific for NO_2 provide the most promising basis for satisfying the measuring requirements for the fastest possible response to a rapidly changing environment and the Ceiling Exposure Limit imposed by some regulators in a small compact package wearable by welders in a manner that does not compromise safety and work activity. However, the potential for cross-reactivity of the NO_2 sensor to contaminants in the welding plume was not known prior to this study. Of the gases known to be present in the plume during welding on aluminum alloys, ozone, in particular, is potentially capable of reaction with the solution in the sensor (Biosystems, 2004; Dräger, 2009). Reaction by ozone would produce a greater signal than expected and hence a false positive indication of concentration of NO_2. A false positive indication of concentration, while seemingly beneficial, could have major implications in respirator selection and use, and also could impose major constraints and difficulties on work practices.

The sensors in the handheld instruments used in this study utilized electrochemical reactions to detect NO_2. The lowest level displayed by these instruments is 0.1ppm. This level is barely acceptable for assessing exposure against the TLV but is better than the option offered by colorimetric detector tubes and other color-based technologies. Gases in the air diffuse into the sensor across a membrane and into the solution inside. Reaction between gas molecules and chemicals in the solution produces an electrical current that is interpreted as concentration (Biosystems, 2004; Chou, 1999; Dräger, 2009). As with colorimetric detector tubes, electrochemical sensors are susceptible to error due to cross-reaction involving other substances present in the atmosphere under examination. This situation can have serious repercussion for compliance with very low Exposure Limits. Cross-reaction potential of sensors produced by different manufacturers is unknown.

1.3 Research Strategy

Air pollution instruments are large, bench-top units. They are unsuitable for measurement in normal workplace environments because of size, tethering to a 110 Volt electrical outlet, and the inability to measure exposure in the breathing zone. The minimum time required to obtain a reading from this type of instrument is one minute.

This instrument can, however, provide a measure of the concentration of NO_2 in the presence of ozone and the other gases that are present in the welding process, and can act as a cross-reference to other measurement technologies. This capability offers the means to determine the relative response of the sensor/instrument implementations offered by different manufacturers. This determination will identify capability of these instrument(s) to respond in an acceptable manner to exposures during welding. What is needed is a means to obtain and present an atmosphere representative of the welding environment simultaneously to all of the instruments.

2. Method

2.1 Location

This work occurred at a shipyard located in Vancouver, British Columbia, Canada during fabrication of large ship structures from aluminum alloys. Structures created during fabrication have geometric configurations ranging from simple to complex. Welding occurred under open, partially enclosed, semi-enclosed, and completely enclosed conditions.

2.2 Welding Parameters

The hull portion of the vessel was fabricated using Pechiney Rhenalu 5383-H321 plate (thickness ranging from 6 to 25mm). The extrusion materials were 6082-T6 and 6061-T6 alloys (Swint, 2000). Fabrication of the hull was occurring during the sample period. The 5083 alloy (thickness as little as 2.5mm) was utilized in areas throughout the vessel other than the hull. Primary welding equipment used on this project (169 units) was the ESAB SVI 450 CV/CC (ESAB Canada, Mississauga, ON) power source with the MIG 4HD ultra pulse wire feeder using a push/pull gun operated in the pulsed GMAW mode. The ESAB-A2 tractor and CV/CC 652 power source were used on flat groove welds throughout the project. Table 1 describes welding conditions (Swint, 2015). The shield gas used during this work was argon. Welding activity met requirements of CAN/CSA W47.2 (CSA Group, 2011).

Table 1. Welding parameters during sampling for NO_2

Parameter	Current Amperes	Voltage Volts
GMAW		
horizontal fillet weld (5083 base material, ER-5183 wire, 1.2mm diameter)	190 to 240	24 to 25
vertical up fillet weld (5083 base material, ER-5183 wire, 1.2mm diameter)	160 to 190	24 to 25
overhead fillet weld (5083 base material, ER-5183 wire, 1.2mm diameter)	180 to 220	24 to 25

Notes:

• Current shall not vary more than ± 15%.

• Voltage shall not vary more than ± 10%.

• When using 6061 base material, current and voltage are higher.

• CSA-CWB W47.2 Aluminum (CSA Group, 2011) was followed during this work.

2.3 Sampling Procedures

The first part of this study involved identification of a detection technology capable of performing satisfactorily in the welding environment. A starting-point was comparison of detection technologies as implemented in different instruments described in literature made available by manufacturers for testing and resources listed on the Internet. This information provided the basis for identifying the strengths, weaknesses and limitations of each technology when compared against concepts discussed in the Introduction. This initial screening provided the basis for rapid exclusion of some of the technologies.

The more advanced part of this evaluation determined performance of the instruments when subjected to the actual welding plume. A container for collecting the welding plume was created from a 1m piece of stainless-steel tube, 12mm in diameter, two lightweight, polyethylene plastic bags one inside the other, and a 20L plastic pail (Figure 1). The tube and the inner bag were connected together using duct tape. The second bag was mounted outside the first to contain leakage in the event of burn-through or other failure. The bag and tube were mounted onto the lid of the 20L plastic pail and positioned inside. This assembly and the lid were sealed using duct tape.

Figure 1. Plume collection apparatus showing the stainless-steel collection tube, polyethylene bag used to store the plume and the plastic pail used to hold the vacuum created by the vacuum cleaner. The vacuum created by the vacuum cleaner in the airspace of the plastic pail inhaled the plume into the storage bag

Interior surfaces of the collector bag and tube were aged by exposure for 16 hours to a high level of ozone from the discharge of the bench-top analyzer (Thermo Environmental Instruments Inc., Model 42C, NO-NO$_2$-NO$_x$ Analyzer, Franklin, MA). The approximate concentration of ozone in the discharge from the analyzer was 0.5%. Normally the instrument discharges through a canister containing charcoal to remove the ozone prior to discharge into the room.

Samples were collected through the stainless-steel tube into the sample bag using the suction from a portable vacuum cleaner. The opening of the tube was positioned in such a way as to collect only the plume. The hose from the vacuum cleaner was connected to the pour spout of the pail. This suction evacuated the airspace outside the bag to create the vacuum needed to inhale the plume into the sample bag (Figure 2).

Figure 2. Collecting the plume into the stainless-steel collector tube and polyethylene storage bag using the vacuum created in the airspace of the pail outside the storage bag by the vacuum cleaner

Note: Absence of protective gloves on the hands of the sample collector is an unsafe practice.

Sampling of the plume occurred under various conditions and at various distances from the arc. The sample bag was emptied prior to collection of the next sample using a portable pump operating at 2L/min. Prior to entering the pump, air inhaled from the bag passed through a large respirator cartridge containing charcoal to remove the ozone and to protect the pump.

The hand-held instruments used in these tests were the Dräger Pac III (Dräger Safety, Pittsburgh, PA), Biosystems Toxi Ultra (Biosystems, Inc., Middletown CT) and AIM Model 4501 (IST-AIM Corp., Richmond, BC). These instruments contained electrochemical sensors for NO_2 reflective of types currently and previously available in the marketplace. Inspection indicated that the sensor in the Dräger instrument was manufactured by Dräger and the sensor in the Biosystems instrument and the AIM instruments, by City Technology, Portsmouth, England. The lowest level displayed by the hand-held instruments was 0.1ppm. These instruments and the bench-top analyzer were calibrated using a source of NO_2 of known concentration prior to and after these measurements.

The hand-held instruments, the inlet tube of the bench-top analyzer and the inlet tube connecting to the portable sampling pump were positioned into a 4L polyethylene bag. Interior surfaces of this bag also were previously exposed overnight to ozone at high concentration, as described. (Loss due to reaction by ozone and other gases on these surfaces posed no consequence to this evaluation.) The instrument enclosure was emptied and purged thoroughly with room air prior to the start of each sample run. Just prior to the start of a test, all of the instruments were activated and allowed to stabilize. The inlet to the instrument bag was then connected to the stainless-steel tubing of the sample collector bag (Figure 3). Tests were performed as soon as possible following sample collection. The delay necessitated by moving from the welding area to the office in which measurement occurred and connecting the sample bag to the instrument bag was typically 2 to 3 minutes.

Figure 3. Polyethylene bag housing the hand-held instruments under test. The stainless-steel tubing at the upper left connected from the polyethylene storage bag to the instrument bag. The Teflon tubing at the lower right connected to the benchtop instrument used for comparison against the hand-held instruments. The plastic tubing at the lower left connected the instrument bag to the portable pump used to purge the instrument bag at the end of the test

The intent of the assembly described here was to maximize turbulence around the sensors of the instruments and to assure fresh supply of sample to the inlet of the bench-top analyzer. The exhaust flow created by the inlet pump of the analyzer (0.7L/min) and the portable sampling pump (2 L/min) emptied the sample collection bag in 10 to 15 minutes. The quantity of plume in the sample collection bag depended on the duration of the weld and the extent of inflation of the sample bag created by the vacuum cleaner.

3. Results

Table 2 provides results from sampling for NO_2. Results reported here were those stored in the datalogger in each instrument. Typically, the concentrations recorded by the instruments increased rapidly to a plateau level. Spurious higher values sometimes appeared on the plateau. Results reported here are typical maximum concentrations.

Generally, results provided by instruments containing the two types of electrochemical sensing technology were approximately the same and slightly less than the concentration measured by the bench-top analyzer. At the levels of NO_2 measured here, these differences do not appear to be significant deterrents to use of the hand-held instruments in this application. Within the group of instruments containing electrochemical sensors, results generally were consistent. No instrument read consistently higher or lower than the others, despite the fact that the

sensors originated from two manufacturers. The Biosystems and AIM implemention of the City Technology sensors produced similar results.

Table 2. NO_2 levels in welding plumes (argon-shielded GMAW)

Location/Description	Measured Concentration (ppm)			
	Thermo Electron	Dräger	Biosystems	AIM
5cm above and to the side of the arc; automatic welding machine	0.2	0.2	0.2	0.2
10cm above and 5cm to the side of the arc; automatic welding machine	0.2	0.3	0.2	0.2
5cm above the arc; manual (production) welding in booth in the Welding School	1.5	1.5	0.9	1.7
20cm above the arc in the plume at front of shield in breathing zone; manual (production) welding in booth in the Welding School	0.1	0.0	0.1	0.1
15cm horizontally from the arc in the plume; manual (production) welding in booth in the Welding School	0.5	0.7	0.5	0.6
25cm from the arc, in path of plume; stitch (manual) welding inside structure	0.2	0.3	0.3	0.4
50cm from the arc, in the plume; stitch (manual) welding on the keel	0.5	1.0	0.6	0.7
over-the-shoulder sample, 20cm from the arc, in the plume; stitch (manual) welding on the keel	0.1	0.1	0.2	0.3
over-the-shoulder sample, 25cm from the arc, in path of plume; stitch (manual) welding inside structure	0.2	0.2	0.4	0.5
over-the-shoulder sample 50cm from the arc, not in path of plume; stitch (manual) welding inside structure	0.2	0.3	0.3	0.4

The concentrations of NO_2 measured in welding plumes collected during GMAW (MIG welding) in the region in space approachable by the breathing zone of a welder generally were considerably less than the Ceiling of 1ppm mandated as an Exposure Limit in some jurisdictions (WorkSafeBC, 2018). Many of the levels equalled or exceeded the current TLV-TWA of 0.2ppm (ACGIH, 2018).

The concentrations obtained in different locations differed considerably from each other and showed no consistent pattern based on distance from the arc. The concentration of NO_2 remained steady and did not decrease as expected with distance from the arc. The cross-section of the plume increases with distance above the arc. The absence of a predictable pattern highlights the difficulty intrinsic in using fixed locations in laboratory simulations for predicting exposure to contaminants during welding. This observation also highlights the importance of a datalogger in the monitoring instrument as a means of gathering information about the interaction between the distance of the arc and the plume from the torso, the orientation of the welder and the geometry of the structure on which work is occurring.

4. Discussion

The first part of this study documented considerations involved in the decision about selection of the best technology to use for measuring exposure to NO_2 in a hazardous industrial environment when several are available. Usually the decision is straight-forward. This is not the case during welding because of the complex nature and requirements of this environment. These include the hazards of process; the need for protection of the worker and the sampling device; the need to position the sensing element of the sampling device in a specific location; the need for unhindered movement by the worker; the characteristics and demands of the signal to be measured; and the potential for interferences in the measurement.

These results indicate general consistency in concentration between instruments containing optical sensors and electrochemical sensors in the environment in which argon-shielded arc welding of aluminum alloys is occurring. The results also suggest the absence of interference by other substance(s) in the plume in the measurement of NO_2 and the suitability of any of the current handheld instruments containing similar electrochemical sensors in this application.

Assessment of exposure to NO_2 during welding is difficult. At least three mechanisms can influence the concentration of NO_2 at a particular point in space at a particular moment in time:

• NO, the precursor of NO_2 forms through reaction of oxygen and nitrogen on hot surfaces (NIOSH, 1988; Perkins, 1974; Seinfeld & Pandis, 1997). The weld and surrounding metal provide considerable heated surface outside the region of the shield as the weld progresses along the seam. Reaction to form NO on metal surfaces occurs at 1000°C (Spiegel-Ciobanu, 2009).

• Reaction between NO and oxygen and/or ozone as occurs outside the gaseous shield converts NO to NO_2. As well, NO present in some shield gas mixtures to destroy ozone, in turn supplies the precursor for creation of additional NO_2 (Seinfeld & Pandis, 1997). Observation shows that the plume forms a cone during arc welding that widens at approximately 20 degrees as distance from the arc increases. Increase in the cross-sectional area of the plume decreases the concentration of NO, ozone, and NO_2 in the plume.

• Finally, the geometric relationship between the torso of the welder, position of the arc and the geometric configuration of the structure all influence the quantity of the plume in the breathing zone.

The samples obtained during this work and tabulated in Table 2 illustrate the complexity of assessing exposure to NO_2 during gas-shielded arc welding from readings obtained in fixed locations as in this situation during real work and in fixed locations created in laboratory simulations. One possible interpretation of the data in Table 2 is that the relatively constant concentration of NO_2 at increasing distance from the arc and the gaseous shield occurred because of increased production of NO_2 coupled with enlargement the surface area of the cross-section of the plume. The plume contains a mixture of NO, NO_2, argon, ozone and atmospheric oxygen and nitrogen (NIOSH, 1988). Reaction between NO and ozone creates NO_2 and depletes the level of ozone. Situations during which aging is potentially demonstrable included plume rise in open air and stagnation in poorly ventilated structures. (Aging has the meaning of change occurring in the composition and chemistry of the plume with the passage of time following generation.)

The first two samples in Table 2 demonstrate the possible aging effect during plume rise. The concentration of NO_2 at twice the height in the plume was the same. The concentration of NO_2 in the second sample was considerably greater than would be expected due to divergence of the plume with distance from the source. The plume rises in the shape of a cone. Hence, the cross-sectional area of the plume increases with increasing height. The only explanation for the concentration of NO_2 to remain constant is production of NO_2 within the plume. An explanation consistent with production of NO_2 within the plume involves oxidation of NO by ozone and/or by oxygen.

The second examples suggesting an aging effect were observed in situations where stagnation was occurring. Stagnation occurred within the confines of the welding booths in the Welding School and in poorly ventilated ship structures. Despite the presence of a local exhaust system in the welding booths in the Welding School, stagnation became possible when the system was not used for collection or the collector arm was positioned inappropriately and/or ineffectively.

Some of this situation is attributable to the necessity to maintain the hemispherical gas shield around the arc. Removal of the gas shield by turbulence induced by local or general exhaust ventilation destroys the weld. As a result, the welder has a considerable disincentive to utilize local exhaust ventilation to collect and remove the plume.

Assessment of exposure to airborne contaminants during welding is technically challenging. This situation arises for several reasons. First is the need to ensure that the welder is protected apropriately against welding hazards. The welding helmet is an integral part of this protection. The welding helmet must fit as designed around the face and neck and not be forced partly open in order to accommodate the measuring equipment. The necessity to position the sampling instrument to obtain a sample representative of exposure must not compromise protection provided by welding protective equipment.

The second reason results from the design of these instruments. Few instruments are designed to sample effectively in the challenging and potentially destructive environment created during welding. There are two fundamental design options regarding sensor position in compact, hand-held instruments. The first option positions the sensor on the external surface of the instrument. Obtaining the sample requires exposure of the surface of the instrument and the sensor to the rigors of the environment including the hazards for which the worker is receiving protection from the welding helmet. This placement puts the instrument and the sensor highly at risk from damage. Portable instruments positioned in the breathing zone of the welder can interfere with and compromise the protective function of the welding helmet.

The second option in instrument design is to bring the sample to the sensor. This choice uses an internal or compact external pump and a sampling probe able to be positioned in the breathing zone remote from the body of the instrument. A pump provides the ability to position the intake of the sampler in the breathing zone without hindering use of welding protective equipment and protects the instrument against physical damage. An add-on, external pump adds to the volume of the instrument. This creates difficulty in positioning the instrument in the pocket of a pair of coveralls.

An additional important feature in these devices is an internal datalogger. The datalogger provides a minute-by-minute record of the exposure profile. This record is invaluable for identifying, investigating, and quantifying unexpected conditions in the environment in which work is occurring. Datalogging sometimes can assist in detection of additional substances not anticipated in the assessment of the environment. A datalogger also is essential for assessing compliance with requirements of a Ceiling Exposure Limit for NO_2.

The best position for these instruments is the upper pocket of a pair of coveralls. This positioning locates the sensor in the breathing zone and enables the wearer to hear the alarm. Small instruments will not compromise protection worn by the welder.

The welding environment is highly destructive to these instruments. They require protection against spatter and UV emissions and protection against dislocation during movement. Experience has shown that the fabric of the protective clothing provides the protection needed in this environment. Protection against dislocation during movement is achievable by secure closure of the pocket. Protection of the instrument against the hostility of the welding environment imposes a substantive barrier against diffusion of gases. The only practical solution to this reality is involvement of a sampling pump and an in-line filter to prevent entry of particulates. Positioning in the pocket and use of a sampling train (Figure 4) also enables use of a sacrificial sampling probe located on the shoulder or lapel in the breathing zone.

Figure 4. Suggested sampling configuration for NO_2. The instrument is installed into the upper front pocket of the coverall. Additional protection against contact with spatter and exposure to UV radiation is required using duct tape. The probe is held in place in the breathing zone by duct tape. The filter prevents entry of particulates into the sensitive internal pathway inside the instrument. The wearer can easily hear the alarm. The datalogger captures events during the period of exposure for later review

5. Conclusions

Any of the portable instruments examined during this study and their future iterations would be satisfactory for assessing worker exposure to NO_2, given the consistency of results compared to the air pollution analyzer and considerations about positioning in the breathing zone. Aging of the plume during increase in cross-sectional area and rise in the airspace of a building and accumulation in poorly ventilated structures are important concerns in the evaluation of exposure to NO_2.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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