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Local Exhaust Ventilation for the Control of Welding Fumes in the Construction Industry—A Literature Review

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Arc welding is a common unit operation in the construction industry, where frequent changes in location and welding position make it more difficult to control fume exposures than in industries where fixed locations are the norm. Welders may be exposed to a variety of toxic airborne contaminants including manganese (Mn) and hexavalent chromium (CrVI). Local exhaust ventilation (LEV) is a well-known engineering control for welding fumes but has not been adopted widely in the construction industry. This literature review presents data on the performance of a variety of LEV systems for welding fume control from the construction (five references), shipyard (five references), and other industries. The studies indicate that LEV can reduce fume exposures to total particulate, Mn, and CrVI to levels below currently relevant standards. Field studies suggest that 40–50% or more reduction in exposure is possible with portable or fixed LEV systems relative to natural ventilation but that correct positioning of the hood and adequate exhaust flow rates are essential. Successful implementation of extraction guns for gas metal arc welding (GMAW) and flux core arc welding has been demonstrated, indicating that a successful balance between extraction airflow and shielding gas requirements is possible. Work practices are an important part of achieving successful control of fume exposures; in particular, positioning the hood close to the arc, checking exhaust flow rates, and avoiding the plume. Further research is needed on hood size effects for controlling welding fume with portable LEV systems and identifying and overcoming barriers to LEV use in construction.

Keywords: construction; local exhaust ventilation; welding

INTRODUCTION

Welding and related hot processes such as thermal cutting can generate a variety of potentially hazardous airborne contaminants including metal fumes containing manganese (Mn) and/or hexavalent chromium (CrVI), ozone, oxides of nitrogen, and carbon monoxide among others. There are many different types of welding, and it is a common operation in a variety of industries. Some of the more prevalent welding processes in construction include shielded metal arc welding (SMAW or stick), gas tungsten arc welding or tungsten inert gas (GTAW or TIG), gas metal arc welding or metal inert gas (GMAW or MIG), flux core arc welding (FCAW), air carbon arc cutting (scarfing), and oxyacetylene torch cutting. A large number of construction trades weld intermittently or may use oxyacetylene torches for thermal cutting (e.g. carpenters, laborers, glaziers). A smaller number specialize in welding and may weld routinely (e.g. pipefitters, boilermakers, sheet metal workers, and ironworkers).

Recent concerns over Mn and neurological disease [see e.g. Notice of Intended Changes for Mn,

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American Conference of Governmental Industrial Hygienists (ACGIH, 2011)] and CrVI and cancer [Code of Federal Regulations (OSHA 2006)] have renewed efforts to control welding fumes to lower levels. The use of local exhaust ventilation (LEV) as a primary engineering control for welding fume is well established and design guidelines exist. Recommended capture velocities for exterior hoods designed to control welding fumes are in the range of 100–170 fpm (0.51–0.87 m s^{-1}) (ACGIH, 2010). The LEV configurations for welding vary depending on whether a fixed site for the work exists or whether a mobile hood is required for work conducted at changing locations. The latter situation is common in the construction industry and dictates the need for a flexible, mobile LEV solution.

The concentration of airborne contaminant inhaled by a worker is determined by the contaminant generation rate and the airflow field that transports it into the breathing zone. LEV eliminates or reduces the fraction of contaminant that makes it into the breathing zone and may induce a flow of clean air for additional protection. The design and position of the local exhaust hood together with the flow rate of air, fume generation rate, level of enclosure, arc-to-breathing zone distance, and work practices largely determine the worker's exposure for a given type of welding. The fume generation rate depends upon the type of welding being done, the arc time, and various process parameters, especially the current density (amperes per cross-sectional area of electrode). The fume composition is a function of the constituents of (i) the consumable electrodes, (ii) the base metals, (iii) fluxes, and (iv) any coatings that may be on the metals. The type of welding may also influence the fume composition (AWS, 1979).

As part of an effort to facilitate adoption of successful engineering controls for welding fumes in the construction industry, this paper presents a literature review of studies that document the performance of LEV for welding processes either in the construction industry or in industries having tasks thought to be relevant to construction. Information pertinent to the performance of the systems is also presented, including work practices or the practicality of the design. The reader is encouraged to consult the original references for details too numerous to include within the scope of this review.

METHODS

Online searching of several databases (Pub Med, Library of Congress, and Web-of-Science) was conducted with End-Note software (Thompson Reuters, 2010) using keywords: welding, construction industry, exposure, LEV, and ventilation. This yielded 1182 references dating from 1949 to 2010, which were further screened for LEV in the abstracts and titles. This resulted in 42 remaining references, which were reviewed for exposure data of some type to assess the LEV performance. Online searches with Google identified the four US Navy studies used here. A search of the National Institute for Occupational Safety and Health (NIOSH) Health Hazard Evaluation online database using keywords LEV and welding for the construction industry did not return any documents. The presence of personal exposure data on the welders was the main criterion for including a given reference in this review. Although one cannot be certain on the completeness of the literature identified, every effort was made to be comprehensive.

The studies identified here generally fell into two broad categories: experimental investigations and field studies. The experimental studies involved controlled settings that paired as many factors as possible (worker, location, amount of welding done, etc.) except for the presence or absence of the LEV. This allowed the efficacy of the LEV to be judged using the differences in exposures. The field trials were uncontrolled and the presence of confounders (e.g. exposures from surrounding operations) and random effects made it more difficult to address the efficacy of the LEV but provided a real-world test of effectiveness.

Personal exposures and percent reductions to various welding fume constituents served as the performance metrics. When personal exposure levels were available, they are compared to current occupational exposure levels (OELs): i.e. the ACGIH Threshold Limit Value (TLV®) (ACGIH, 2011), the NIOSH Recommended Exposure Level (REL) (NIOSH, 2005), and the Occupational Safety and Health Administration Permissible Exposure Level (OSHA). Mn, CrVI, iron, carbon monoxide, and total particulate (TP) were the most common agents identified in the studies. Table 1 provides the current OELs for each substance when available.

RESULTS

The results are organized into four major sections below. The first three include information on the LEV system in addition to exposure measurements and are classified based on industry type. The first section presents material specific to the construction industry; the second contains studies thought to be relevant to construction, such as shipbuilding; and

Table 1. Current values for relevant OELs.

	Mn, mg m^{-3}	CrVI, μg m^{-3}	TP, mg m^{-3}	Iron oxide, mg m^{-3}	Carbon monoxide (ppm)
NIOSH REL	1.0	1	N/A	5	35
ACGIH TLV	0.2	10 (insoluble) 50 (soluble)	10	10	25
OSHA PEL	5.0	5	15	10	50

N/A, Not Applicable; OSHA PEL, Occupational Safety and Health Administration Permissible Exposure Level

the third group is all other industries. The fourth and final major group contains only qualitative information on the LEV system, i.e. whether it was present or not, and may contain any type of industry. Data in this final section are less helpful in reaching conclusions about factors that influence the effectiveness of LEV in the field but do document exposure reductions. The last two sections are further divided into two subparts: one dealing with fume extraction guns (FEG) and the second subpart with other types of LEV. A variety of different statistics are reported in the different publications and the data are reported here as they were in the cited papers.

LEV-welding studies in construction

Specific studies of welding fume exposures in the construction industry that assess the effectiveness of LEV are limited, with only four identified here. In a field study, Susi *et al.* (2000) reported on personal exposure measurements of metal fumes to boilermakers, ironworkers, and pipefitters during welding and thermal cutting from 1995 to 1996. In 1996, two different local exhaust systems were used: 'one was a small portable unit with flexible duct for both capturing and exhausting contaminant' and it was not equipped with filtration. The second larger unit was equipped with a High-Efficiency Particulate Air (HEPA) filter, and the hood was attached to a movable elbow joint. The mean TP exposure when local exhaust was used was 1.99 mg m^{-3} ($n = 6$); for natural ventilation, the result was 5.39 mg m^{-3} ($n = 56$); for no ventilation, 9.45 mg m^{-3} ($n = 1$); and for mechanical ventilation, 1.72 mg m^{-3} ($n = 16$). Here 'mechanical ventilation' refers to fans and blowers used to mix the air or dilute the concentration as opposed to LEV where an exhaust hood is located proximal to the source to remove the fumes prior to entry into the breathing zone. The authors compared the combined mechanical and LEV results with the combined natural and no ventilation data and found a statistically significant difference ($P = 0.0001$). Subsequent analysis of these data by building trade (Flynn and Susi, 2010) suggested that LEV and mechanical ventilation for the pipefitters reduced TP and Mn exposures by 21% (3.3 versus 2.6 mg m^{-3}) and 12% (0.076 versus 0.067 mg m^{-3}), respectively. For boilermakers and ironworkers, there was no LEV, only mechanical ventilation, and the results were mixed depending upon the degree of enclosure.

In a simulation study (aspects of both field and experimental studies) conducted at the Boilermaker's National Apprentice Training School, two LEV systems were evaluated for controlling exposures during stainless steel SMAW (NIOSH, 1997). The welding was done by three different welders in a semi-enclosed tank outside the building. Flat welds were conducted on a 9-inch (23 cm) long flat piece of steel (base plate) supported on workhorses in the tank. One LEV system (Unit 1) was a Plymovent MEF mobile fume extractor with a 2-m arm; the flexible duct from the slightly conical hood was 6.25 inches (15.9 cm) in diameter. The system had a recommended hood flow of 570–706 cfm (0.27–0.33 m^{3} s^{-1}). The other system, a Plymovent BSFM-2101 (Unit 2), was a portable fan with similar arm but not a conical hood. Neither LEV was equipped with a filter; however, exhaust was discharged via flex duct to the outside of the tank. The hoods were placed 3 inches (7.6 cm) from the end of the 9-inch (23 cm) plate. Measurements of capture velocities were made for each unit at 6, 9, and 12 inches (15.2, 22.9, and 30.5 cm) in front of the hoods. The results are presented below by unit.

Unit 1. No hood flow was indicated. The measured capture velocities were 120, 60, and 30 fpm (0.6, 0.3, and 0.15 m s^{-1}), respectively. Based on personal exposure measurements of total fume, the investigators concluded that Unit 1 was not significantly different from natural ventilation ($P = 0.64$).

Unit 2. The study reported a hood face velocity of 1820 fpm (925 m s^{-1}) at the hood face center of Unit 2 and concluded the airflow was 390 cfm (0.18 m^{3} s^{-1}). The measured capture velocities were 300, 220, and 50 fpm (1.5, 1.1, and 0.25 m s^{-1}). The personal exposure measurements (total fume) indicated Unit 2 was significantly better than Unit 1 ($P = 0.03$) and was significantly better than no ventilation at all ($P = 0.006$). For CrVI, Unit 2 was significantly better than no ventilation at all ($P = 0.02$). Unit 2 resulted in lower CrVI exposures than Unit 1, but this did not reach statistical significance ($P = 0.09$).

Seven out of 10 personal samples collected when ventilation was used (for either unit) were in excess of the TLV® at the time (5 mg m^{-3}) indicating inadequate effectiveness. The researchers noticed a tendency of welder 2 to be consistently positioned outside of the plume, while welder 1 was often in the plume; as expected, welder 1 had significantly higher exposures. The researchers also indicated that wind may have diminished the LEV performance; air currents of 20–40 fpm (0.1–0.2 m s^{-1}) in the partially enclosed tank were cited. Based on the capture velocity measurements made, Unit 1 clearly had inadequate airflow and Unit 2 appears to be low as well. The failure of the systems to maintain capture velocities above 100 fpm (0.51 m s^{-1}) over the entire length of the base plate where the welding took place is likely a major factor in the marginal performance.

In addition to welding conducted in the tank, some welding was done indoors where real-time particle measurements (light-scattering device) and personal exposures (filter samples), were used to evaluate the ventilation. The filter data showed a factor of 5 reduction in CrVI when LEV was used compared to when none was employed. The real-time personal data showed a factor of 4 reduction in total fume and a factor of 3 for area monitoring when LEV was used.

Meeker *et al.* (2007) conducted both experimental and field evaluations of a commercially available portable LEV unit (Miniflex Portable High Vacuum Fume Extraction Unit, Lincoln Electric, Cleveland, OH, USA). The unit was equipped with a small bell-shaped hood and was operated at approximately 103–110 cfm (0.049–0.050 m^3 s^{-1}). The unit had a rated filter efficiency of 99.97%. The experimental testing was done in a semi-enclosed booth at a local training center of the Plumbers and Pipefitters union. Small sections of 6-inch (15.2 cm) diameter carbon steel pipe were welded (SMAW) using E6010 and E7018 electrodes. Each run was 50–60 min in duration and consisted of two welds; arc times were on the order of 30 min. Five randomized trials were done for each condition of LEV and no LEV; a single welder performed all tasks. The experimental results showed statistically significant reductions ($P = 0.002$) in mean Mn exposures on the order of 75% (0.051 versus 0.013 mg m^{-3}). TP reductions were about 60% (1.83 versus 0.74 mg m^{-3}, $P = 0.002$). The experiment demonstrated the efficacy of the LEV for reducing fume exposures.

The field survey also involved stick welding (SMAW) on carbon steel pipes by journeyman pipefitters installing 6- to 20-inch (15–51 cm) chiller pipes in a commercial construction project. Some thermal cutting and grinding processes were also being performed in the area and likely contributed to the exposures. LEV was used by one of the two welders on a random assignment basis for 7 of 8 days of full-shift sampling. Geometric mean Mn exposures in the field test were reduced by 53% (0.097 versus 0.046 mg m^{-3} $P < 0.05$). Geometric mean exposures to TP were only reduced by 19% (5.0 versus 4.5 mg m^{-3}) and were not statistically significant. It was hypothesized that tasks other than welding may have contributed to the total dust exposures in the field. The authors noted that when LEV was in use, none of the field samples exceeded the current TLV® for Mn of 0.2 mg m^{-3}. However, when LEV was lacking, two out of the nine samples were above this level.

In a second study, Meeker *et al.* (2010) conducted an experimental evaluation of the same Miniflex unit described above for the control of CrVI exposures. The experimental testing was conducted very much as described in the first study. Welding was done on 6-inch (15.2 cm) diameter stainless steel pipe, using GTAW for the root pass and SMAW for the fill and cap pass. The Miniflex bell-shaped hood was placed 2–3 inches (5.1–7.6 cm) above the weld. The LEV reduced the median hexavalent chrome concentrations by 68% (1.93 versus 0.62 μg m^{-3} $P = 0.02$). The mean and median values for hexavalent chrome were below the current NIOSH REL (of 1 μg m^{-3}) when LEV was in use, but both values exceeded this limit when LEV was absent.

In addition, this study reported on two field studies involving LEV for the control of CrVI. The field surveys took place in 2007 and 2008 and involved a variety of thermal cutting and welding tasks on carbon and stainless steels. In the first study, the LEV systems were portable, either a Lincoln Miniflex with a slot type hood or a Donaldson Torit Easy Trunk system (Donaldson Co., Minneapolis, MN, USA). In the 2008 study, a larger centralized scrubber/fan unit with attached ducts and hoods was used (Ventex, Tampa, FL, USA). Airflow measurements on the systems were not made. Among all samples, the median CrVI exposure was lower with LEV than without, but did not reach statistical significance. However, for SMAW samples, the median CrVI exposure without LEV was at 6.65 μg m^{-3}, while with LEV it was 1.25 μg m^{-3}, and the difference was statistically significant ($P = 0.03$).

The studies described above are specific to the construction industry and provide important information on the efficacy and effectiveness of LEV for controlling welding fume. The data suggest that substantial reductions in total fume, Mn, and CrVI are possible with LEV, and in some cases result in exposures below current OELs. They also indicate that work practices are important and that the position of the hood and airflow rate are critical in achieving successful control. Processes that occur in the vicinity of welders are also critical and to achieve effective control with LEV the surrounding environment must also be taken into account. Uncontrolled operations, or the discharge of unfiltered exhausts in the vicinity of the welders, will obviously impact the effectiveness of any LEV controls in use. The studies are limited, however; sample sizes are small, only a limited number of welding tasks have been examined, and field studies are few in number.

LEV-welding studies in the shipyard industry

The use of LEV to control welding fumes has been documented in a variety of industries which have tasks and types of welding similar to those in the construction industry. This is particularly true in the shipyard industry since the work environment may be very similar to construction work encountered during industrial rehabilitation and maintenance work. For example, welding inside tanks and process vessels may closely resemble welding in a ship hull, in that both involve work in enclosed, often poorly ventilated areas. In 1998, the US Navy released a detailed evaluation of several engineering controls for welding fume in the shipbuilding industry (US Department of the Navy, Naval Surface Warfare Center, 1998). The report contained 46 personal samples for exposure to multiple metals including chromium, CrVI, nickel, and Mn. Detailed information on controls and ventilation was available in some cases, and 10 different control/ventilation types were identified. Welding types included FCAW ($N = 29$), GMAW ($N = 7$), GTAW ($N = 5$), and SMAW ($N = 5$).

Due to the small sample sizes for GMAW, GTAW, and SMAW, the effect of ventilation was explored only for FCAW. Seven different control/ventilation configurations were identified as follows: (i) Fume Extraction Gun (FEG), (ii) fixed fume extraction systems, (iii) portable fume extraction and general supply ventilation, (iv) low-fume welding wires, (v) low-fume welding wires and general supply ventilation, (vi) low-fume welding wires and portable fume extraction, and (vii) low-fume welding wires and portable supply air ventilation. Table 2 gives the mean value of the personal exposures measured for these different control/ventilation systems for the FCAW. The FEG seemed to perform better than, or comparable to, the other choices, despite the small sample size and confounding factors.

A subsequent study (US Department of the Navy, Naval Surface Warfare Center, 2001) consisted of an extensive review of FEG and focused on the development of a new lightweight unit for shipyard use. The report provided a literature review documenting the history of the FEG for GMAW and FCAW welding guns. The authors report that shielding gas flows for such guns range from 12 to 21 l min^{-1} and that the exhaust flows range from 35 to 60 cfm (0.017–0.028 m^3 s^{-1}). The exhaust hoses are reported as 1–1.5 inches (2.5–3.8 cm) in diameter with 50–80 inches (1.27–2.03 m) of water static pressure at the gun. The exhaust nozzle-to-work piece distance may be from 0.25 to 1.25 inches (6.3–31.8 mm) depending on the weld type. The extract nozzles are generally an annular slot located about 0.5 inch (1.3 cm) behind the shielding gas supply outlet or an exhaust chamber with multiple holes spread out over the surface. Multiple references and measurements by the authors on three commercially available units suggested that fume extraction efficiencies varied by the weld position and extraction flow rate. The overhead fillet weld and the horizontal

Table 2. Control/ventilation effect on average fume exposures in shipyard FCAW (US Department of the Navy, Naval Surface Warfare Center, 1998).

Control/ventilation	Chromium, μg m^{-3}	Nickel, μg m^{-3}	Mn, mg m^{-3}	CrVI, μg m^{-3}
FEG (n = 4)	0	0.58	0.07	0.07
FFES (n = 3)	29.7	6.73	0.06	0.5
PFE & GSV (n = 2)	1.35	0.65	0.40	0.91
LFWW (n = 7)	37.2	8.2	1.69	1.69
LFWW & GSV (n = 4)	2	0	0.49	0.16
LFWW & PFE (n = 6)	5.4	2.1	2.19	0.80
LFWW & PSAV (n = 3)	2.7	1.9	0.57	0.63

FFES, fixed fume extraction systems; PFE & GSV, portable fume extraction and general supply ventilation; LFWW, low-fume welding wires; LFWW & GSV, low-fume welding wires and general supply ventilation; LFWW & PFE, low-fume welding wires and portable fume extraction; and LFWW & PSAV, low-fume welding wires and portable supply air ventilation.

bead-on-plate weld were associated with extraction efficiencies of 27–37%, while flat, bead-on-plate, and horizontal fillet welds had extraction efficiencies that ranged from 54 to 91%. Ergonomic factors, especially the weight of the gun, were viewed as significant drawbacks as evidenced by worker ratings of the guns.

In a project report (Harris, 2000) on current shipyard practice, CrVI exposures were reported for a variety of conditions (open, enclosed, or confined spaces), welding type, and base metal and for either natural ventilation or LEV. The local exhaust parameters were not well characterized, sample sizes were small, and the results were mixed. Exposure levels for the LEV treatments were lower in only 7 of the 16 comparisons (Table 3). In three out of the four cases that had at least five samples per ventilation condition, the LEV average exposure was lower. A more recent study (US Department of the Navy, Naval Surface Warfare Center, 2007) of shipyard CrVI exposures by ventilation type and space size is presented in Table 4. The mean exposures were less when LEV was used across all space sizes; however, the effect was most dramatic in the smaller sized spaces less than 2000 ft^3 (56 m^3) in volume.

LEV-welding studies in other industries

The following studies describe welding outside the construction industry. However, since some of the welding processes described are also used in construction and they provide some quantitative evaluation of LEV performance, they have been included in this review.

Fume extraction guns. Smargiassi *et al.* (2000) looked at exposures to welders in the manufacture of large excavation machinery. The facility employed mainly GMAW using an AIRMIG model 520, Henlex gun with integrated exhaust system designed for 70–80 cfm (0.03–0.04 $m^3\ s^{-1}$) of extraction. Shielding gas was carbon dioxide at a flow rate of 30–35 cfh (0.000236–0.000275 $m^3\ s^{-1}$). Ten kilograms per day per worker of flux cored wire containing 1–5% Mn were used. Occasional SMAW with E48018 electrodes (1–3% Mn) was also performed but much less frequently than GMAW. Mild and carbon steels were the base metals. The welders found that use of the integrated exhaust system in

Table 3. Shipyard CrVI exposures by ventilation type, confinement level, base metals, and welding type (Harris, 2000).

Process and material	Average worker exposures (μg m^{-3}) (*N*)					
	Open		Enclosed		Confined	
	Natural	LEV	Natural	LEV	Natural	LEV
SMAW mild steel	0.3 (8)	0.41 (4)			0.45 (2)	1.18 (5)
SMAW HY80 steel			0.29 (7)	0.8 (1)		
SMAW HY100 steel	0.34 (10)	1.10 (4)	0.53 (3)	0.75 (4)		
SMAW stainless			16.4 (10)	4.63 (8)		
GMAW Ni alloys	0.35 (2)	1.3 (1)				
GMAW stainless	0.91 (3)	0.94 (4)	1.79 (1)	1.5 (7)		
GTAW Ni alloys			0.15 (4)	0.27 (2)		
GTAW stainless	0.87 (36)	0.1 (2)	1.0 (20)	0.14 (7)		
FCAW steel	0.35 (20)	0.2 (11)	0.2 (6)	0.06 (1)	0.21 (5)	0.6 (10)
Oxy fuel cutting HY100					0.2 (2)	0.1 (2)

Table 4. Shipyard CrVI exposures by space volume and ventilation condition (US Department of the Navy, Naval Surface Warfare Center, 2007).

	Exposures (μg m^{-3}) by space size and ventilation					
	<2000 ft^3 (56 m^{-3})		2000–5000 ft^3 (56–140 m^{-3})		5000–10 000 ft^3 (140–280 m^{-3})	
	LEV	General/Natural	LEV	General/Natural	LEV	General/Natural
N	4	10	3	11	7	7
Minimum	0.02	0.05	0.19	0.05	0.01	0.21
Maximum	0.05	30.2	0.39	1.20	3.29	3.10
Mean	0.04	9.15	0.30	0.32	0.62	1.43

semi-enclosed environments altered the quality of the weld; this appeared to be related to the weight of the gun and requirements to maintain vertical gun positions for effective exhaust. Mn exposures over the ACGIH TLV® of 0.2 mg m^{-3} were common on the welding of large pieces but not on smaller parts where the extraction gun seemed to work better, presumably due to the ease of maintaining the gun in a vertical position.

Wallace *et al.* (2001) examined the effectiveness of fume extraction welding guns at a manufacturing facility making steam ovens, using GMAW, GTAW, and FCAW, on carbon steel. Mixing fans were common throughout the plant. Two different systems were examined; the first had the hood incorporated directly into the welding gun, with ventilation and shielding gas lines encased in a single tube leading from the gun. The second had a non-ventilated gun but with a Tweeco suction attachment connected to the gun nozzle; exhaust and gas lines were separate here. In both cases, exhausts were attached to 3-inch (7.6 cm) diameter ducts dropped from a main header. All exhaust was filtered and discharged outside.

To assess the effectiveness of the ventilation, the researchers compared exposures to total welding fume during FCAW with ventilation on and off, the mean exposure with ventilation in use was 6.31 mg m^{-3} (n = 13) and with it off it was 24.15 mg m^{-3} (n = 3). The researchers measured capture velocities on the order of 3500–4000 fpm (17.85–20.40 m s^{-1}) 1 inch (2.5 cm) from the gun nozzle and noted that the recommended values were 100–200 fpm (0.51–1.02 m s^{-1}) and that higher values might disrupt shielding gases. The investigators noted that there was significant concern among some welders that the LEV was removing shielding gas and increasing the probability of poor welds. This led some welders to adjust the extraction flows via the choke collar or to increase shielding gas flows to minimize this risk. The investigators concluded that further work needed to be done to determine the best position for the collar to get the correct airflow to control exposures.

The relationship between shielding gas flow rate and the capture velocity induced at the welding point is a critical variable in the successful implementation of extraction ventilation integrated with welding guns. Iwasaki *et al.* (2005) state that 'Unless the capture velocity exceeded a 0.8 m s^{-1}, the formation of blow holes in the welded metal could be prevented at shielding gas flow rate of 20 l min^{-1}'. At shielding gas flow rates of 30 l min^{-1} and 40 l min^{-1}, they noted that the critical values of capture velocity at the arc point were 1.2 and 1.6 m s^{-1}, respectively. They also noted the effectiveness of open-type push–pull units for some welding applications.

In a separate study, Gregory *et al.* (1971) described a successful FEG design to control zinc fumes from a GMAW-CO_2 welding process. They noted a shielding gas flow rate of 30 cfh (0.0002 m^3 s^{-1}); the fume extractor was described as an annular space 1/8 inch (0.3 cm) wide around the gun nozzle, which projected out about the same distance from the lip of the extractor. The system was rated for 155 cfm (0.073 m^3 s^{-1}) at 22 inches (56 cm) of water, but it was unclear what the actual flow rate of extraction air was. The evaluation was not based on any sampling but visual evaluation of the capture as 'complete'.

Other local exhaust. Several studies provided quantitative information on LEV systems for welding fume control that were not extraction guns. Zaidi *et al.* (2004) reported on the performance of two units; one designated as portable and the other as mobile. The portable unit weighed 50 kg and had an unflanged metallic cone-shaped hood 30 cm in diameter, while the mobile unit was 150 kg with an unflanged square hood 38 cm. The use of the portable LEV unit reduced the concentration of Mn in the breathing zone on a side from 22.16 (±20.9) to 8.25 (±4.5) μg m^{-3}. The flow rate of the mobile unit was noted as 5.66 m^3 and the portable was listed as 4.24 m^3. The study suggested that ventilation would reduce exposures, but without correct flow rate information and/or some capture velocities, it is difficult to evaluate.

Kromhout *et al.* (2004) summarized 10 welding surveys conducted from 1983 to 2003 in the Netherlands. Over 1258 measurements from 426 workers and 325 companies were included. The authors conducted a statistical analysis that suggested company type was the most important factor. They noted 'When the effectiveness of LEV was taken into account it became evident that distance of LEV to the weld was a very strong predictor of personal welding fume concentrations. Adjustable well-positioned LEV resulted in a 40% reduction of exposure concentrations'.

A more recent publication by Liu *et al.* (2011) provides further information on the variation of welding fume exposures. In particular, mean exposures to TP and Mn for several different industries were reported, although sample sizes ranged from 3 to 642. These values in milligrams per cubic meter (TP, Mn) were as follows: construction (5.49, 0.132), manufacturing (10.5, 0.476), shipyard (3.99, 0.836), railroad (7.53, 1.42), and automobile (1.19, 0.09).

Jafari and Assari (2004) reported on the performance of LEV and general ventilation in a moderate-sized welding shop with 11 welding stations. In two of the welding stations, slot hood designs were used and in the nine others plain opening hoods were employed. The combined use of LEV and general ventilation consistently reduced iron oxide and carbon monoxide exposures below the respective current TLVs, whereas respirable dust and ozone exposures on occasion exceeded current TLV levels. The mean value of volumetric airflow through all LEV hoods was 34.7% of the recommended (ACGIH) values. Hood face velocities ranged from 1.25 up to 12.3 m s^{-1} and hood flows were reported from 401 to 1006 m^3 s^{-1} but these values are unreasonably high, perhaps by a factor of 1000. The general exhaust ventilation was 35.5% of the ACGIH recommended value. Table 5 presents a summary of the exposures and ventilation data.

Welding studies with qualitative LEV information

Several studies present information on the effects of LEV on welding exposures but do not provide quantitative information on the LEV systems, indicating only whether it was present or not. As noted above, this type of information is generally inadequate for reaching conclusions about the effectiveness of any given LEV design, although the studies overall indicate lower average exposures when ventilation is present versus when it is not.

In a study of shipyards and plants making boilers and pressure vessels, Smith (1967) examined exposures from low-hydrogen SMAW welding. The work took place in various locations that were classified as confined, enclosed, or open. Confined indicated a totally enclosed compartment generally less than 2000 ft^3 (56 m^3) in volume with access through a manhole less than 30 inches (76 cm) in diameter. Enclosed spaces had at least one open side with volumes in excess of 2000 ft^3 (56 m^3); open indicated welding in large workshops or in the open air. Table 6 presents the results of fume measurements taken with and without LEV in enclosed and confined spaces. The author noted that total fume concentrations inside a boiler with no ventilation were 48.2, 52.7, 56.1, and 88.3 mg m^{-3} while LEV reduced levels from 6.3 to 35.3 mg m^{-3} (n = 7). It was observed that the LEV hoods [generally 4-inch (10.2 cm) diameter ducts] had 'sufficient capture velocities at distances not greater than 2 inches (5.1 cm) from the arc'. However, no velocity data were presented.

Steel (1968) also examined shipyard welding and flame cutting and compared breathing zone concentrations of zinc fume for enclosed processes with and without ventilation (note LEV was not specified). Out of 48 ventilated processes examined, 19 were over the TLV® at that time (5 mg m^{-3}). Approximately 17 unventilated cases were examined, and 12 were over the TLV® (graphical estimation). The author stressed the importance of LEV being used with dilution ventilation when possible and suggested 'flanged fishtail extraction at each individual welding point'. Steel goes on to specify a maximum allowable distance for the hood from the fume

Table 5. Summary exposure statistics for combinations of LEV and general exhaust ventilation in a welding shop from Jafari and Assari (2004).

Ventilation settings			Iron oxide, mg m^{-3}	Respirable dust, mg m^{-3}	Ozone ppm	CO ppm
General	LEV					
ON	ON	Minimum	0.00	1.03	0.01	5.00
		Maximum	5.20	5.76	0.03	10.0
		Mean	2.17	3.53	0.02	7.50
		Standard deviation	1.65	1.83	0.01	2.11
OFF	ON	Minimum	1.08	1.20	0.01	6.00
		Maximum	6.77	7.30	0.04	13.0
		Mean	2.86	4.48	0.03	9.68
		Standard deviation	1.88	2.23	0.01	2.10
ON	OFF	Minimum	4.70	5.10	0.01	15.0
		Maximum	10.2	24.8	0.05	20.0
		Mean	7.13	11.1	0.04	18.9
		Standard deviation	1.78	5.57	0.01	1.70
OFF	OFF	Minimum	7.13	8.93	0.03	22.0
		Maximum	16.5	48.5	0.07	32.0
		Mean	10.4	20.9	0.05	27.0
		Standard deviation	2.49	14.2	0.01	3.26

Table 6. Shipyard total fume exposures by enclosure and LEV (Smith, 1967).

Environmental condition	Sample size (*N*)	Concentrations, mg m^{-3}		
		Maximum	Minimum	Median
Confined				
No LEV	66	112.0	1.0	21.0
LEV	40	41.9	6.3	17.6
Enclosed				
No LEV	76	57.6	0.7	10.2
LEV	25	77.8	1.4	5.6

source of 1 ft (0.30 m), a 1000 cfm (0.47 m^3 s^{-1}) flow rate, and a hood face velocity of 1500 fpm (7.62 m s^{-1}).

Van der Wal (1985) looked at selected metal and gas exposures in Dutch welding industries. Some limited manual metal arc (MMA) welding on unalloyed steels provided 3-h time weighted average total welding fume exposure data which allowed comparisons by LEV status to be made. Eleven measurements without LEV ranged from 2.4 to 11 mg m^{-3} and had a mean of 6.3 mg m^{-3}. Four measurements with LEV that was poorly positioned above the head ranged from 7 to 17 mg m^{-3} with a mean of 13 mg m^{-3}. Five measurements with LEV used correctly ranged from 1.9 to 4.6 mg m^{-3} and had a mean of 3.0 mg m^{-3}.

In a subsequent paper, Van der Wal (1986) reported on chromium, nickel, and gas exposures to Dutch plasma welders and cutters. Some information on the effect of LEV was included. Two plasma cutters both working on stainless steel, one without LEV at the torch and one with LEV, showed fairly consistent exposure ratios of about 3:1 (no LEV versus with LEV) for total fume (6.0–2.1 mg m^{-3}), CrVI (3–1 μg m^{-3}), total chromium (100–35 μg m^{-3}), and nickel (120–40 μg m^{-3}) in the breathing zone; area samples showed similar results. There was some confounding since the plasma cutter without the ventilation had an arc time of 20 vesrus 15 min for the one with LEV but that would only be expected to account for about 30–40% of the exposure differences assuming all else was equal. The study also noted high ozone levels in microplasma welding due to the extremely close distance between the torch and the welders face, i.e. less than 20 cm.

Dryson and Rogers (1991) examined four plasma cutters and measured their exposures to total chromium, iron, nickel, total mass, and carbon monoxide. The ventilation was designated as doors and windows only no-exhaust (A), overhead exhaust (B), or extraction at bench level. The results indicated that while the extraction at bench level generally appeared superior, the confounding of the different base metals limited any definitive conclusions.

Korczynski (2000) conducted personal monitoring on welders in eight welding companies in Manitoba, Canada. GMAW on mild steels and GTAW on aluminum were the primary types of welding. Of the 42 welders monitored for fume, 62% were above the Mn TLV® of 0.2 mg m^{-3}. Half of the companies had only general ventilation provided by wall and/or ceiling fans; 40% of the companies had no ventilation other than natural airflow; one company had an LEV system with movable hoses at each welding station; and hood face velocities were reported at 350–400 fpm (1.79–2.04 m s^{-1}) in one case and 50–75 fpm (0.26–0.38 m s^{-1}) in another. A large portable HEPA unit was not used; the welders reported that it was heavy and cumbersome to move. A welding gun with integrated extraction was observed with a flow rate of 30 cfm (0.014 m^3 s^{-1}); the welder reported that it was cumbersome and the filters clogged frequently.

Ulfvarson (1981) provided an extensive survey on exposures to Swedish welders. There was some consideration of the effects of LEV, which in general showed the tendency for exposures to be lower when LEV was used than when not, although in several cases the differences were not statistically significant. Cases that showed statistically significant effects for LEV included metal active gas welding of steel (identified as GMAW), a 65% reduction in average dust contents compared to no LEV, and the MAW of stainless steels for both total dust and chromium trioxide. The chromium exposures were on average a factor of 2 over the relevant OEL in effect at the time (0.03 mg m^{-3}) with LEV, but over a factor of 6 without it. The author noted that in later studies of metal arc welding on steel, LEV reduced average dust concentrations to 42% of what they were without LEV, and while LEV had a marked effect at reducing oxide of nitrogen exposures, it was not as effective with ozone (perhaps due to formation of ozone at locations remote from the arc).

In a review of CrVI exposures in US industries, Blade *et al.* (2007) identified several welding studies with LEV and exposure measurements. The evaluation of the LEV systems was qualitative in nature and one case involved the construction industry. The welding tasks involved mainly stick welding and grinding indoors. Some MIG welding was done as well; steel and galvanized piping and sheet metal were the base metals. Full-shift sampling for hexavalent chrome revealed a range of $<$0.04–0.42 μg m^{-3} with four values below the limit of detection. The

LEV was characterized as effective in the indoor welding. Eight other welding cases, not in the construction industry, were noted and are summarized in Table 7.

Matczak and Chmielnicka (1993) looked at chromium exposures generated during MMA welding on stainless steels in four Polish industrial plants. Plant A manufactured equipment for power stations, plant B was in the chemical industry, and plants C and D were metal industries. All plants had dilution ventilation with blowing and exhaust, but only plant C had LEV at the welding sites. The content of the welding fumes on average did not appear to vary too much from plant to plant, although within plant B the chromium content ranged from 13.5 to 22%. The authors noted the highest total chromium content in plants A and B where 'the work was performed in a half closed area without local exhausts and in a forced body position'. The fewest number of samples exceeding the TLV® for soluble CrVI (1 out of 18) was at the plant with LEV, i.e. plant C which also had the lowest value at 1.3 times the TLV®. The value reported as a TLV® for soluble CrVI was 0.025 mg m^{-3}.

In a review of a large data set of welding exposures, Flynn and Susi (2010) reported on the differences between welding exposures when exhaust was present and absent. In general, exposures were elevated when LEV was not used compared to cases when LEV was present; the mean exposures (no LEV to LEV) were as follows: TP (4.6 versus 3.0 mg m^{-3}), iron (2.1 versus 1.2 mg m^{-3}), and Mn (0.16 versus 0.11 mg m^{-3}).

DISCUSSION

LEV is a primary engineering control available to minimize worker exposures to toxic airborne contaminants. However, its use on construction sites seems infrequent despite evidence of elevated exposures to hazardous metal fumes. This may account for, at least in part, the scarcity of relevant publications describing LEV effectiveness in this industry. However, ventilation use will likely grow for controlling welding fumes and gases in construction

Table 7. CrVI exposures in welding (Blade *et al.*, 2007).

Operation/Standard Industrial Classification	Process description job title	Exposure to Cr(VI), µg m^{-3}	Comments/other exposures	Ventilation
MIG welding stainless/3444	MIG welder	2.8, 5.2, $N = 2$	Exposures inside welding helmet (2.6, 1.0)	LEV but poor capture
MIG, TIG plasma arc/3444	Welding supervisor	2.0, 3.7, $N = 2$	Exposures inside weld helmet (8.5, 3.2)	LEV but poor capture No LEV on plasma arc
MIG on stainless/3494	MIG welder	0.2–5.5, $N = 4$ not automated	MIG automated <0.07, <0.08	LEV and fume extractor but capture poor
Cutting torch and carbon arc/4499	Ship demolition, burner	<0.07–27.0, $N = 14$, GM = 0.35; GSD = 5.4	Some steel with chromate paint	Mostly outside no LEV Inside no LEV only gen
Welding and cutting on alloys/3324	Foundry work, Welder	0.37 – 22.0, $N = 4$	MIG, TIG, SMAW, carbon arc gouging	No LEV Cutting on 25% Cr alloy Heavy workload
TIG welding on sheet metal/3444	TIG welder	0.65, $N = 1$	Inside welding helmet	LEV but poor capture
SMAW, FCAW, TIG, and others/3731	Shipyard welder	0.19–0.96, $N = 3$ tight spots	<0.04–0.22, $N = 15$ open areas	Some LEV in tight spots via flex duct relocations
TIG, dual shield, fusion submerged arc, plasma/3494	TIG welder	All below LOD, $N = 6$		Welding fume extractor LEV poor capture No LEV on plasma
Stick, MIG piping and sheet metal/1711	Welder	<0.04–0.42, $N = 7$ (4 < LOD), mainly stick	<0.04–0.53, $N = 8$ (6 < LOD), outdoor welding	One indoor had effective LEV

GM, geometric mean; GSD, geometric standard deviation; LOD, limit of detection.

given increasing health concerns related to Mn and CrVI exposures.

The construction-specific studies by Meeker *et al.* (2007, 2010) illustrate that a portable fume extraction system can produce reductions in Mn concentrations in the field for SMAW welding on the order of 50% and to levels below the current TLV®. The more modest reduction in TP in the field of 19% highlights the importance of identifying and controlling other sources of exposure to the worker. Similarly, LEV reduced CrVI levels in the field to levels below the NIOSH REL of 1 μg m^{-3}.

Engineering controls are often designed to work without much input from the worker; however, for most welding operations, work practices remain a critical part of a successful intervention. This was evident in the study at the boilermaker training facility (NIOSH, 1997) where one welder was careful about positioning his face away from the plume and the other was not. Positioning oneself outside of the welding plume is an important work practice to instill in apprentice welders as early as possible. However, as a practical matter, positioning where one stands relative to the weld plume may be difficult to control given natural air movements and the degree to which job requirements and the work environment constrain movement.

An important factor over which workers have some control is the position of the LEV hood relative to the point of fume generation. The need for repositioning of LEV equipment to different locations on a job site as well as frequent repositioning of portable exhaust hoods with respect to the weld are challenges to the effective use of LEV in the construction industry. The air velocity drops off very rapidly in front of local exhaust hoods, especially small ones, and thus they must be located close to the arc to be successful. For small exhaust hoods, e.g. 2–3 inches (5.1–7.6 cm) in diameter, relatively small distances (e.g. 0.5–1 inch) can make a dramatic change in the capture velocity at the arc location. Consider a 3-inch (7.6 cm) diameter flanged circular hood positioned 1.5 inches (3.8 cm) from the arc and inducing a capture velocity there of 100 fpm (0.51 m s^{-1}). If the hood is repositioned such that it is 2.5 inches (6.5 cm) away, the capture velocity drops to about 50 fpm (0.25 m s^{-1}). Thus, worker knowledge and behaviors associated with correct positioning of the exhaust hoods are essential for LEV to be effective.

In addition if the bead length is comparable to the hood size, then there may be significant changes in capture velocity over the length of the bead. As the arc moves, fume may escape more easily if capture velocity drops off. Once the arc moves out of the immediate influence of the hood velocity, field escape of the fume is more likely. Larger exhaust hoods are less sensitive to an absolute change in distance and are able to exert a more powerful flow field over a greater distance than small hoods can. This feature was first described by Brandt (1947) and later explored with theoretical calculations for particle stopping distance under the influence of different-sized hoods (Flynn, 2003).

It is not clear from the literature examined here how larger hoods might improve the performance of portable LEV systems for welding relative to smaller hoods. There will be trade-offs as the smaller systems offer flexibility in constrained spaces and may be more mobile and maneuverable in some situations, but they are likely to be less forgiving if not positioned precisely. These multiple and sometimes conflicting considerations may make proper selection of LEV equipment difficult for those in the industry charged with making decisions on equipment purchase and use. Industrial hygienists can play an important role in identifying both the factors and equipment that should be considered for particular welding applications. In addition, they can provide input to welding apprenticeship programs with regard to understanding and communicating key concepts related to selection and use of LEV.

The need for repeated repositioning of the exhaust hood is one reason that extraction guns are appealing. The hood is positioned on the gun and once the airflow rate is balanced to work correctly vis-a-vis the shielding gas requirement, the positioning issue is largely resolved, at least for some welding positions. Extraction guns appear to work well and be feasible for FCAW and GMAW but have not been integrated into SMAW operations as of yet. Where extraction guns are used, the literature identifies poorer performance for overhead or vertical welding. The welding plume is buoyant due to the thermal energy imparted to it from the arc. As it rises vertically, extraction gun inlets that are positioned to receive the plume can be expected to perform well. However, as the position of the weld and gun change, the buoyant plume may be in opposition to the extraction flow and reduced performance and increased exposure may result. This may limit extraction guns in many construction applications where overhead or variable position welds are required.

There are numerous barriers to the use of LEV in construction (e.g. cost, mobility, productivity concerns). However, one identified in this review, and encountered by the authors, is concern among welders about LEV and other forms of ventilation interfering with shielding gases. The ACGIH Industrial

Ventilation Manual (ACGIH, 2010) suggests that capture velocities over 150 fpm (0.76 m s^{-1}) at the arc may disturb shielding gases. This appears to be in reasonable agreement with the data reported above by Iwasaki *et al.* (2005). Additional studies documenting worker exposures, ventilation nozzle flow rates, and shielding gas flow rates that result in high-quality welds would be helpful.

CONCLUSIONS

The literature reviewed here supports the fundamental engineering principles of maintaining adequate airflow and positioning the hood close to the point of fume generation. However, in some cases, specific constraints make successful control of the fumes challenging and dependent upon work practices. The literature shows that LEV can produce substantial reductions in welding fume exposures relative to natural or general ventilation when used correctly.

FEG provide protection in FCAW and GMAW operations although the issue of disturbing the shielding gas is important. Correct balance of airflows and location of the nozzle are possible to minimize this problem, however. The data suggest that the capture efficiency of these guns depends upon the weld position, with vertical or overhead welds having the lowest fume capture efficiencies and flat welds the highest. The weight of the extraction guns must be minimized to facilitate ergonomics and worker acceptance. Given the prevalence of stick welding in construction, which requires frequent electrode replacement, these systems may have limited application.

Further field research is needed to evaluate the effectiveness of different LEV systems and hood sizes for the portable fume extraction systems used in various tasks by multiple construction trades. Minimizing the weight of virtually all the equipment including the portable extraction units is desirable to minimize hand and arm strain, permit mobility, and facilitate worker acceptance of the controls. Although LEV can produce significant fume reductions, work practices are important and training in correct hood positioning, as well as avoiding the plume, is necessary. Maintenance of the systems with periodic inspection and checks for adequate hood flow via pressure gauges or other devices is needed. Training in these work practices and procedures are likely to be most effective among apprentices before work habits have become engrained.

The paucity of current literature on LEV effectiveness in general, and for construction operations in particular, speaks to the need for more applied research in this area. It is not well known how transferable information regarding LEV performance from other industries is to construction. Nonetheless, the studies described in this review illustrate important principles that are universal to LEV systems regardless of what industry is using them. Research aimed at identifying barriers to LEV use and methods for overcoming those barriers are important areas for research as well.

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REFERENCES

ACGIH. (2010) Industrial ventilation—a manual of recommended practice. 27th edn. Cincinnati, OH: ACGIH.

ACGIH. (2011) Threshold limit values for chemical substances and physical agents & biological exposure indices. Cincinnati, OH: ACGIH.

AWS. (1979) Fumes and gases in the welding environment. Miami, FL: AWS.

Blade LM, Yenken MS, Wallace ME *et al*. (2007) Hexavalent chromium exposures and exposure-control technologies in American enterprise: results of a NIOSH field research study. J Occup Env Hyg; 4: 596–618.

Brandt AD. (1947) Industrial health engineering. New York, NY: Wiley & Sons.

Dryson EW, Rogers DA. (1991) Exposures to fumes in typical New Zealand welding operations. N Z Med J; 104: 365–7.

Flynn MR. (2003) On the inertial range of particles under the influence of local exhaust hoods. Ann Occup Hyg; 47: 151–6.

Flynn MR, Susi P. (2010) Manganese, iron and total particulate exposures to welders. J Occup Env Hyg; 7: 115–26.

Gregory EN, Herrshaft DC, Cole JF. (1971) Fume extraction when welding zinc coated steels. Am Ind Hyg Assoc J; 32: 170–3.

Harris I. (2000) Reduction of Worker Exposure and Environmental Release of Welding Emissions, Task 1 – Current Shipyard Practice, NSRP ASE Project, Edison Welding Institute Project No. 43149GTH.

Iwasaki T, Fujishiro Y, Kubota Y *et al*. (2005) Some engineering countermeasures to reduce exposure to welding fumes and gases avoiding occurrence of blow holes in welded material. Ind Health; 43: 351–7.

Jafari A, Assari MJ. (2004) Respiratory effects from work-related exposure to welding fumes in Hamadan, Iran. Arch Env Health; 59: 116–20.

Korczynski RE. (2000) Occupational health concerns in the welding industry. Appl Occup Env Hyg; 15: 936–45.

Kromhout H, Veldhof R, Knoll B. (2004) Determinants of exposure to welding fumes: lessons learned from a database covering a 20-year period. Abstract X2004 Conference: Exposure Assessment in a Changing Environment. Utrecht, The Netherlands. Available at http://www.iras.uu.nl/X2004/programme/showabstract.php?id=205. Accessed 19 February 2009.

Liu SA, Hammond K, Rappaport SM. (2011) Statistical modeling to determine sources of variability in exposures to welding fumes. Ann Occup Hyg; 55: 305–18.

Matczak W, Chmielnicka J. (1993) Relationship between various chromium compounds and some other elements in fumes from manual metal arc stainless steel welding. Br J Ind Med; 50: 244–51.

Meeker JD, Susi P, Flynn MR. (2007) Manganese and welding fume exposures and control in construction. J Occup Env Hyg; 4: 943–51.

Meeker JD, Susi P, Flynn MR. (2010) Hexavalent chromium exposure and control in welding tasks. J Occup Env Hyg; 7: 607–15.

NIOSH. (1997) In-depth survey report: control-technology assessment for welding operations. In Wallace M, Fishbach T, and Kovein RJ, editors. Report ECTB 214-13a.

NIOSH. (2005) NIOSH Pocket Guide to Chemical Hazards. Department of Health and Human Services, Centers for Disease Control, (NIOSH) Publication No. 2005-149. Cincinnati, OH.

OSHA. (2006) Chromium (VI). Code of Federal Regulations Title 29, Part 1910.1026. Washington, DC.

OSHA. Tables Z1, Z2 and Z3. Code of Federal Regulations Title 29, Part 1910.1000. Available at: http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9992. Accessed 20 March 2012.

Smargiassi A, Baldwin M, Savard S *et al*. (2000) Assessment of exposure to manganese in welding operations during the assembly of heavy excavation machinery accessories. Appl Occup Env Hyg; 15: 746–50.

Smith LK. (1967) Fume exposures from welding with low hydrogen electrodes. Ann Occup Hyg; 10: 113–21.

Steel J. (1968) Respiratory hazards in shipbuilding and shiprepairing. Ann Occup Hyg; 11: 115–21.

Susi P, Goldberg M, Barnes P *et al*. (2000) The use of a task-based exposure assessment model (T-BEAM) for assessment of metal fume exposures during welding and thermal cutting. Appl Occup Env Hyg; 15: 26–38.

Thompson Reuters. (2010) End Note software v X.4.0.1 (2010). Carlsbad, CA: Thompson Reuters.

Ulfvarson U. (1981) Survey of air contaminants from welding. Scand J Work Environ Health; 7 (Suppl. 2): 1–28.

US Department of the Navy, Naval Surface Warfare Center. (1998) National Shipbuilding Research Program; welding fume study task no. 3—field evaluation. NSRP 7-96-9 Final Report. Appendices A–C. Available at: http://www.dtic.mil/dtic/search/tr/tr.html. Accessed 20 March 2012.

US Department of the Navy, Naval Surface Warfare Center. (2001) National Shipbuilding Research Program; development of lightweight fume extraction welding guns. Available at: http://oaidtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA452250. Accessed 20 March 2012.

US Department of the Navy, Naval Surface Warfare Center. (2007) National Shipbuilding Research Program Safety and Health Advisory Committee; industry wide survey for hexavalent chromium (CrVI) exposures in shipyard operations. Available at: http://wwwpublic.navy.mil/navsafecen/Documents/OSH/oshdata/OccHlth/NSRP_Hexavalent_Chromium_Exposures-0108.pdf Accessed 20 March 2012.

Van der Wal JF. (1985) Exposure of welders to fumes, Cr, Ni, Cu and gases in Dutch industries. Ann Occup Hyg; 29: 377–89.

Van der Wal JF. (1986) Further studies on exposure of welders to fumes, chromium, nickel and gases in Dutch industries: plasma welding and cutting of stainless steel. Ann Occup Hyg; 30: 153–61.

Wallace M, Shulman S, Sheehy J. (2001) Comparing exposure levels by type of welding operation and evaluating the effectiveness of fume extraction guns. Appl Occup Env Hyg; 16: 771–9.

Zaidi S, Sathawara N, Kumar S *et al*. (2004) Development of indigenous local exhaust ventilation system: reduction of welders exposure to welding fumes. J Occup Health; 46: 323–8.