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Manganese, Iron, and Total Particulate Exposures to Welders

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Welders are exposed to a variety of metal fumes, including manganese, that may elevate the risk for neurological disease. This study examines several large data sets to characterize manganese, iron, and total particulate mass exposures resulting from welding operations. The data sets contained covariates for a variety of exposure modifiers, including the presence of ventilation, the degree of confinement, and the location of the personal sampler (i.e., behind or in front of the welding helmet). The analysis suggests that exposures to manganese are frequently at or above the current ACGIH® threshold limit value of 0.2 mg/m³. In addition, there is evidence that local exhaust ventilation can control the exposures to manganese and total fume but that mechanical ventilation may not. The data suggest that higher exposures are associated with a greater degree of enclosure, particularly when local exhaust ventilation is absent. Samples taken behind the helmet were, in general, lower than those measured outside of it. There were strong correlations among manganese, iron, and total particulate mass exposures, suggesting simple equations to estimate one fume component from any of the others.

Keywords construction trades, manganese exposures, mixed exposures, welding

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INTRODUCTION

A recent literature review⁽¹⁾ documents neurological impairments associated with manganese exposures received during welding operations. Although some studies^(2–4) suggest a link to Parkinson's disease, this finding is controversial and in need of further research. The literature^(5–7) provides evidence of subtler neuropsychological effects in welders, presumably associated with manganese exposures as well. As a result, there is a need to characterize the levels of exposure to manganese and other metals that welders incur as a result of the tasks they perform.

This article presents an analysis of three databases consisting of welding exposures to manganese, iron, and total particulate mass. The focus here is on exposures related to neurological outcomes; however, welding fumes may contain hexavalent chromium, nickel, and other metals that present additional risks, including lung cancer.

Currently, the Occupational Safety and Health Administration (OSHA) does not have a permissible exposure limit (PEL) for welding fumes per se; compliance is based on standards for the individual metals or for total particulate mass. The PEL for manganese is 5 mg/m³ set as a ceiling for total fume and dust, while for iron oxide fume it is 10 mg/m³ set as an 8-hr time-weighted average (TWA). The National Institute for Occupational Safety and Health (NIOSH) considers welding fumes carcinogenic and recommends that exposures be maintained at the lowest feasible level.⁽⁸⁾

From 1974–2004 the ACGIH® threshold limit value (TLV) for welding fumes (not otherwise classified) generated from stick welding or oxy-gas welding of iron, mild steel, or aluminum was 5 mg/m³ as total particulate. This standard was based on placing the personal sampling device behind the welder's helmet.⁽⁹⁾ In 2004, this TLV was withdrawn based on the consideration that welding fume is variable in composition and required more detailed study. From 1948–1959 the TLV-TWA for manganese was 6 mg/m³, and from 1960–1962 it was set at 5 mg/m³. A 1-mg/m³ TLV-TWA for manganese fume came into effect in 1979, and in 1992, the current TLV-TWA of 0.2 mg/m³ was set. ACGIH is currently proposing a change in the limit for manganese to 0.2 mg/m³ for inhalable dust and a 0.02 mg/m³ level for respirable dust with a notation that the TLV is based on “CNS func (neurobehavioral and neuropsychological changes).”^(10, p. 63)

Welding is associated with many job titles or trades in construction, and there are several different types of welding. A variety of exposures can be encountered, and depending on the type of welding being done and the metals being fused, the exposures can be quite different. A significant amount of welding is done on steel. Inevitably, iron and manganese will be present in the base metals being joined and the filler wire being used and, hence, in the fumes that workers are exposed to. The more common types of welding include: stick

or manual metal arc (MMA), flux cored arc welding (FCAW), tungsten inert gas (TIG,) and metal inert gas (MIG). The related processes of arc cutting, gouging, and oxy-acetylene welding/cutting are also of concern.

The objective of this work was to characterize manganese, iron, and total particulate exposures associated with the most common types of welding employed in the construction trades, i.e., MMA, MIG, FCAW, and TIG, although other types of welding are also examined. Although manganese is of current interest, it is not analyzed for in many welding samples; thus, the correlations between it and iron and total mass may be of use in exposure estimation. Iron may also be an important factor in the transport of manganese across the blood-brain barrier.

Several issues are explored here, including the comparability of the data sets, the time dependent nature of exposures, the influence of local exhaust ventilation, the degree of confinement, and the impact of sampler location with respect to the welding helmet. The data sources used here are: (1) The Welding Institute (TWI) online database, (2) the Center for Construction Research and Training - CPWR data set on welding and hot-process exposures, and (3) an OSHA compliance data set for welding.

BACKGROUND

A literature review of studies documenting manganese exposures in welding operations is presented here and summarized in Table I. An excellent overview of welding processes and the associated exposures can be found in Burgess.⁽¹¹⁾ Ranges of exposures to manganese (in mg/m³) for the various types of welding are listed there as: shielded metal (or stick welding), 0.01–1.0; gas metal, 0.01–0.05; gas metal flux-cored, 0.02–2.0; and gas welding 0.01–0.05.

Studies designed to examine the protective effect of the welding helmet on exposure to airborne particles have produced mixed results, although, in general, there has been a tendency for the exposures measured inside the helmet to be lower than those taken external to it. Goller and Paik⁽¹²⁾ noted that iron oxide fume concentrations inside the helmet were 36–71% of those measured outside the helmet, depending on welding type and worker posture. Recent studies have noted more modest and variable results. Liu et al.⁽¹³⁾ observed a mean fume concentration ratio (inside-to-outside the helmet) of $0.9 \pm \text{SD } 0.2$, and note highly variable reductions. Harris et al.⁽¹⁴⁾ concluded that for low-to-moderate exposure environments “sampling outside the helmet may in fact be fairly representative of the actual exposure of the worker.” (p. 380)

One study⁽¹⁵⁾ focused on manganese exposure in welders; 27 full-shift samples for total manganese (MnT), and 20 for respirable manganese (MnR) were collected on 10 workers. The bulk of the welding involved GMAW (gas metal arc welding) with vacuum collection, using flux-cored electrodes containing from 1–5% manganese. The range for the total manganese was 0.027–0.367 mg/m³ with a geometric mean

TABLE I. Summary of Literature Documenting Manganese Exposures in Welders

Source	Welding Descriptions	Manganese Exposures (mg/m ³)
Smargiassi et al. ⁽¹⁵⁾	GMAW and flux cored some ventilation	0.03–0.37 AM = 0.18 (T) ^A 0.02–0.26 AM = 0.11 (R) ^B
Wallace et al. ⁽¹⁶⁾	Various	FCAW: GM = 0.56 GMAW: GM = 0.11 GTAW: GM = 0.003
Susi et al. ⁽³¹⁾	Construction, arc welding, and cutting	0.00–1.31 AM = 0.2 (1995) 0.00–0.47 AM = 0.07 (1996)
Korczynski ⁽¹⁹⁾ Mattorano et al. ⁽²⁰⁾	MIG on mild steel MIG and Stick	0.01–4.93 AM = 0.5 0.046–0.87
NIOSH ⁽²¹⁾ Lu et al. ⁽²⁸⁾	Various, shipyard Vehicle manufacture	0.24–7.33 In car 1.47 ± 0.72 Outside car 0.87 ± 0.7 Near parts 0.47 ± 0.06 0.36
Jafari and Assari ⁽²⁵⁾	Single welder	
Karlsen et al. ⁽²⁶⁾	Shipyard, MMA, stainless steels	0.02–0.12
Bellido-Milla et al. ⁽²⁷⁾	Spanish shipyards	ND–3.89
Crossgrove and Zheng ⁽²⁹⁾	Welders in China construction	0.42–3.05 (20% of data) 25.7 maximum
Ellingsen et al. ⁽³⁰⁾	Shipyard and heavy machinery	Manual: GM = 0.12 MIG: GM = 0.13 Automated: GM 0.02
Meeker et al. ⁽³³⁾	Field survey results pipefitters SMAW	Mn (No LEV) AM = 0.12 Mn (With LEV) AM = 0.06

^AT = total mass.

^BR = respirable mass.

of 0.144 mg/m³ and a GSD of 2.1, the respirable range was 0.020–0.258 mg/m³ with a geometric mean of 0.094 mg/m³ and a GSD of 2.0. The arithmetic means for total and respirable manganese were reported as 0.18 and 0.11 mg/m³, respectively.

In a study on the effectiveness of fume extraction guns for welding operations, the authors conclude “the geometric mean

data show that the use of ventilation generally resulted in lower exposures than when no ventilation was used.”^(16, p. 775) They found that the type of welding used is especially important in determining fume exposures. They noted that, in general, flux-cored arc welding (FCAW) had the highest exposures, followed by gas metal arc (GMAW), and then gas tungsten arc (GTAW). The geometric mean exposures to manganese (in mg/m³) for the various welding processes are as follows: FCAW = 0.56 (N = 20); GMAW = 0.11 (N = 11); and GTAW = 0.003 (N = 10).

In the case of flux-cored welding, comparisons for the effectiveness of ventilation were made. The results indicated that with ventilation on, the geometric mean exposure to Mn was 0.49 mg/m³, with ventilation off 0.96 mg/m³. The ventilation was either a Lincoln integrated unit with the extraction built into the gun, or a conventional unit with a Tweco suction attachment. The highest exposure measured was to a worker performing flux-cored welding without ventilation at 32.91 mg/m³ total fume. This exposure was more than three times higher than any other measurement made. The authors concluded that using substitute welding methods instead of FCAW was the most important factor for control.

In a control technology assessment of welding operations at the Boilermaker's National Apprentice Training School investigators concluded that welders were overexposed to hexavalent chromium, arsenic, total chromium, iron, manganese, and nickel.⁽¹⁷⁾ The study was conducted in an enclosed area meant to simulate a process vessel or boiler. Investigators further stated that while local exhaust ventilation (LEV) did help reduce exposure levels, the reductions were not completely controlled and the effect of wind and position of the welder may have adversely impacted ventilation. The investigators found, not unexpectedly, that the welder who “had his face in a direct line with the welding plume” had higher exposures than the worker who “kept his face at an angle to the plume.”^(17, p. 17)

The American Welding Society⁽¹⁸⁾ conducted detailed experimental studies on fumes and gases generated during various welding processes and also looked at local exhaust ventilation. This is a good resource for identifying electrode and fume composition by element, fume generation rates for various welding types, and other technical information. Graphs are presented indicating the effect of worker position relative to the local exhaust hood and welding operation, the influence of cross drafts, and other important variables. The studies were performed with a welding simulator under controlled conditions so many real-world considerations were omitted. The study calls attention to the importance of current density (amps per cross sectional area of the electrode) as an important determinant of fume generation rate.

Harris et al.⁽¹⁴⁾ conducted a controlled study of manganese exposure during shielded metal arc welding (SMAW) in a 2200 cubic foot chamber. The welder used E6010, E7018, and Mangjet electrodes containing 5.4%, 1.4%, and 48.0% manganese in the flux, respectively. Measurements of total fume and total and respirable manganese were made with dilution airflows through the chamber ranging from 150–2300 ft³/m.

Measured concentrations were, in general, inversely proportional to dilution flow as expected, and significantly higher manganese exposures (about a factor of 5) were noted with the Mangjet electrode. At the highest dilution airflow (close to 2200 ft³/m in all cases), the total manganese measured inside the helmet was 0.14 mg/m³, 0.16 mg/m³, and 1.5 mg/m³ for the E6010, E7018, and Mangjet electrodes, respectively. Area respirable samples in the vicinity of the welder were above 0.2 mg/m³ in all cases. Total and respirable manganese measured inside the helmet were very close, indicating most of the manganese inside the helmet was respirable.

Harris and colleagues⁽¹⁴⁾ concluded that “welders and their helpers continuously welding using SMAW in an enclosed or restricted space, such as that described here, would consistently be exposed to manganese above the 2003 proposed TLV of 0.03 mg/m³, and often in excess of the current TLV of 0.2 mg/m³.”^(p. 381) They further point out that the 2000 ft³/m dilution ventilation recommended by OSHA 29 CFR 1910.252 (c)(2) may not be sufficient to control manganese exposures. Consistently higher respirable manganese area samples relative to the welder personal samples indicated that those in the vicinity of the welding may be at significant risk as well.

Korczynski⁽¹⁹⁾ reported on the results of a study by the Workplace Safety and Health Branch in Manitoba, Canada, involving eight companies using MIG welding on mild and stainless steels, and TIG on aluminum. Forty-two personal exposure samples for iron and manganese were collected inside the welding helmet. Exposures to manganese ranged from 0.01–4.93 mg/m³ with an arithmetic mean of 0.5 mg/m³ (SD = 0.9). Forty-two percent of the welders were overexposed to manganese based on the ACGIH TLV-TWA of 0.2 mg/m³. Iron exposures ranged from 0.04–16.29 mg/m³ with an arithmetic mean of 3.0 and an SD = 3.5. Only 19% were overexposed to the ACGIH-TLV-TWA for iron of 5 mg/m³. The author noted that only 7% of the welders wore respiratory protection, 40% of the companies had no ventilation system, 50% of the companies used only ceiling or wall fans, and the few local exhaust systems that were found were considered generally ineffective and often times were not used.

One case study of exposures at a ship breaking facility reported several manganese (as well other metals) exposures during stick welding inside a barge tank (n = 5), under the barge (n = 2), and MIG welding under the barge (n = 2).⁽²⁰⁾ For stick welding inside the tank, the 8-hr TWA for total manganese ranged from 0.046–0.87 mg/m³, with four of the samples exceeding the TLV of 0.2 mg/m³; all other samples were below the TLV.

In a NIOSH Health Hazard Evaluation⁽²¹⁾ the authors report personal exposures of welders in a shipyard involved with stick welding, arc gouging, and flux-cored welding primarily on mild steels. Five TWA values were reported for total fume, manganese, and iron, among other fume constituents. Four of the five sample durations were very close to or exceeding 400 min, while one (a confined space sample) was for 99 min. The manganese results ranged from 0.24 mg/m³ to 7.33 mg/m³; iron ranged from 0.98–12.5 mg/m³, and total

fume ranged from 3.15–55.5 mg/m³. The highest values were all associated with the short-term confined space task.

Significant exposures to welding fume have also been reported in the construction industry during excavation support operations when steel crossbeams are welded.⁽²²⁾ Personal samples meeting or exceeding TLV values for total fume, fluoride, and manganese were reported. Verma et al.⁽²³⁾ report excessive total fume exposures due to arc welding, gouging, soldering, and thermal cutting in the construction trades, especially ironworkers, laborers, plumbers, and pipefitters. Exposures as high as 28.3 mg/m³ total fume and 17.3 mg/m³ inhalable were reported.

Oxhoj et al.⁽²⁴⁾ reported on respiratory symptoms and welding exposures in shipyards. They monitored 60 welders with personal samplers and found that about half the welders were exposed to total particulate concentrations exceeding 10 mg/m³ and that the mean composition of the fume was 39.9% iron and 6.3% manganese. Jafari and Assari⁽²⁵⁾ reported exposure to a single welder of 31.1 mg/m³ for iron and 0.36 mg/m³ for manganese. Karlsen et al.⁽²⁶⁾ looked at exposures to shipyard workers while welding on stainless steel using manual metal arc. They were concerned primarily with hexavalent chromium and nickel exposures but also reported iron exposures ranging from 0.3–29.0 mg/m³ and manganese exposures from 0.02–0.12 mg/m³.

Bellido-Milla et al.⁽²⁷⁾ studied welding fume exposures in a shipyard in Spain. They collected 166 personal samples and 14 area samples over a 3-month period at various locations in the facility. The results were reported as means and standard deviations for seven different locations. The mean values for iron ranged from 1.66 to 15.7 mg/m³, and for manganese, they ranged from nondetected to 3.89 mg/m³. The majority of samples exceeded the TLV for manganese. The investigators also looked at exposures with and without fume extractor and found higher exposure when the ventilators were used. They stated “Ventilators are only used in extreme cases and shows that the factory’s ventilation systems do not efficiently remove evolved gases under these conditions.”^(p. 925) Based on optical microscopy, the authors reported that about 45% of the fume was less than one micron in size.

Lu et al.⁽²⁸⁾ examined various biomarkers of manganese exposure among welders performing manual metal arc welding at a vehicle manufacturing site. They found a positive correlation between the number of years working as a welder and serum concentrations of iron and ferritin. They also found an inverse correlation between serum manganese and serum transferrin. Personal airborne manganese exposures for welding inside the vehicles measured at 1.47 mg/m³ (±0.72) and outside the vehicle at 0.87 mg/m³ (±0.7); welding parts near the vehicles produced levels of 0.47 mg/m³ (±0.06). Among 421 work sites in metropolitan Beijing with annual monitoring for manganese, 20% showed airborne Mn concentration between 0.42–3.05 mg/m³, with the highest reported level at 25.7 mg/m³. Seven welders were diagnosed as manganese poisoned.⁽²⁹⁾

Ellingsen et al.⁽³⁰⁾ reported manganese and other metal exposures for welders from a shipyard and a plant that manufactured machinery. All samples were taken behind the welding helmet, and in all, there were 188 measurements made on 96 welders. Results were presented in terms of the type of welding identified as manual, semiautomatic, and automated. From the descriptive information provided, it appears that the manual welding was, in fact, stick welding, the semiautomatic was MIG, and the automatic was robotic flux-cored welding. The geometric means of all the samples (n = 188) for manganese and iron were 0.97 and 0.894 mg/m³, respectively, suggesting that manganese exposures were about 11% of the iron exposures. Geometric mean values for manganese exposures by welding type were reported as: manual 0.121 mg/m³, semiautomatic 0.131 mg/m³, and automated 0.019 mg/m³.

A comprehensive study of manganese and fume exposures to construction workers involved in welding and related hot work tasks was conducted by CPWR in 1995 and 1996 and summarized in two related publications.^(31,32) These data, along with some additional measurements, comprise one of the data sets used in the analysis below. The study by Susi et al.⁽³¹⁾ reported 61 personal exposures to manganese collected during 1995 and 75 measurements in 1996. The 1995 measurements ranged from 0.0005–1.31 mg/m³ with a mean of 0.2 mg/m³, and the 1996 measurements ranged from 0.001–0.47 mg/m³ with a mean of 0.07. The boilermakers had 72% of their samples exceed the TLV, while 15% of the samples on ironworkers and 7% of the samples on pipefitters were over the TLV.

Some local exhaust ventilation (LEV), mechanical blowers, and fans were installed in 1996. Total fume personal exposure measurements (n = 22) collected during tasks with these controls were compared with exposures collected with no ventilation or natural ventilation only (n = 57). The respective means were 1.79 mg/m³ and 5.26 mg/m³, which were significantly different (p < 0.0001). Susi and colleagues concluded that significant health hazards existed from welding and thermal cutting fume, manganese, nickel and chromium VI.

In addition, they noted that “use of local or mechanical ventilation reduced mean exposures to fumes significantly.”^(31, p. 26) Subsequent analysis of the same data set concluded, “Local-exhaust or mechanical ventilation reduced exposure to TP [total particulate] (but not Mn) by as much as 44%, and shielded or manual arc welding increases exposure to Mn (but not TP) by about 80%.”^(32, p. 457)

Meeker et al.⁽³³⁾ examined the effectiveness of a portable local exhaust ventilation system for the control of welding fumes generated during typical tasks in the construction industry. The unit demonstrated a 75% reduction in manganese exposures and a 60% reduction in total particulate exposures in laboratory studies. Field results produced a 53% reduction in Mn exposures and 10% reduction in total particulate. The poorer results with the total particulate exposures in the field were attributed to sources other than welding fume in the workplace (e.g., dust sweeping by adjacent workers).

Due to the different factors addressed in the studies described above, the small sample sizes, and the variety of different types of welding, it was desirable to summarize exposures using some larger data sets with significant numbers of samples in the various covariate categories. Because of the differences in sample durations in the larger data sets examined here, both the total TWAs and the averages based on the number of samples were examined.

METHODS AND DATA SET DESCRIPTION

TWI Data Set

As downloaded, the TWI data set contained 1929 welding samples (many with multiple metals reported) collected from 1973 through 2007 in the United States, U.K., and Canada.⁽³⁴⁾ Measurements from NIOSH Health Hazard Evaluation reports, as well as industry sampling results from shipbuilding, machinery manufacture, and motor vehicle industries were included. The data set was edited by removing all samples not specifically identified as breathing zone samples. Samples characterized as “simulation” or “worst-case” were also deleted, as were “robotic welding” and “resistance welding” samples. Only samples that had a value for the time period sampled were retained; this left 740 samples for analysis (identified here as TWI Data Set #1). For the 14 samples listed as below a detection limit, the exposure was set to one half of this limit. Sample times varied widely from 4 to 839 min. A wide variety of industries were sampled, including shipyards and machine manufacturing; however, construction industries were not sampled in this data set.

Subsequent to the initial data extraction from the TWI data set, it was desirable to examine several determinants of exposure to welding fume. This required utilizing a subset of the above data to create a second data set to look at welding operations that had simultaneous indicators for the presence of local exhaust ventilation (LEV = yes or no), sampler location (behind the welding helmet, yes or no), and also the degree of confinement (confined = A, semiconfined = B, or other = C). The matching on these variables resulted in a second TWI data set that contained 434 samples. Sample durations here varied from 20 to 528 min. This second data set is identified as TWI Data Set #2.

CPWR DATA SET

The CPWR - Center for Construction Research and Training data set consists primarily of total particulate and manganese exposures to construction workers performing welding, brazing, and thermal cutting operations. The data set is overwhelmingly shielded metal arc welding (88% of the identified samples) with a few other varieties (mostly MIG and TIG) comprising the remainder. Other metals including chromium and nickel were also measured but were fewer in number and are not addressed here. The trades involved were pipefitters, boilermakers, and ironworkers. The data were collected over a period from 1995–2007 at 10 job sites and

involved rehabilitation, maintenance, and new construction at a number of facilities, including refineries, pipe fabrication, semiconductor plants, pulp and paper, aerospace, public buildings, and bridges.

Unlike the TWI data, all measurements collected in the CPWR surveys were measured external to the welding helmet. The data contained a variety of information in addition to the exposures, including indicators for ventilation, the degree of confinement, and whether there was continuous or intermittent hot work (welding) involved. This provided the first CPWR data set for analysis (CPWR Data Set #1). A subset of these data (CPWR Data Set #2) was used to examine the correlations between manganese and total particulate. This data set consisted of paired measurements of the TWA concentration of total particulate mass (C_T) and manganese (C_M) on a given individual for a given day. There were 121 paired measurements from 37 pipefitters (PF) taken at seven different facilities. In addition, 37 paired values from 21 boilermakers (BM) at two different facilities were also collected. Data for the ironworkers were excluded from this second data set because of the relatively few paired measurements of total particulate and manganese. This left nine job sites represented in CPWR Data Set #2.

OSHA Data Set

The final data source was obtained from OSHA and consisted of all compliance samples identified as welding from 1978 through early 2008. This data set contained 5339 personal TWA samples of manganese exposure, with a mean of 0.27 mg/m³. The samples were all considered as full-shift samples. A wide variety of industries were represented, and approximately 150 of the 5339 samples examined were in the construction industry. A subset of 504 paired measurements was extracted to examine the correlation between manganese and total particulate mass.

RESULTS

TWI Data Set

Table II summarizes the total TWA exposures in TWI Data Set #1, including the number of samples and the total sample durations. In addition, it presents the sample means based on the simple arithmetic average of the N samples for each metal. Both mean values are reported since there were significant differences in the sample durations. The TWA exposures to total mass, iron, and manganese are 3.85, 2.03, and 0.21 mg/m³, respectively; while the sample averages are in reasonable agreement at 3.81, 2.51, and 0.20 mg/m³ respectively. Considerably more data, both in terms of the number of samples as well as the total sample time, were available for total particulate mass than for either iron or manganese exposures.

Table III identifies the TWA exposures for the more common types of welding in TWI Data Set #1. These levels ranged from 67.6 mg/m³ total mass for plasma arc cutting to 1.1 mg/m³ total mass for TIG welding, with wide disparities

TABLE II. Total TWA Exposures and Mean Values Calculated Based on Number of Samples (TWI Data Set #1)

	Means (mg/m ³)			Number of Samples (N)
	Total TWA	Based on Number of Samples	Total Time Sampled (min)	
Total mass	3.85	3.81	168,012	617
Iron	2.03	2.51	94,859	258
Manganese	0.21	0.20	53,841	140

in both numbers of samples and total durations. Manual metal arc welding (MMA) or stick welding is the most common type of welding and was well sampled relative to the other varieties, with a time-weighted mean total particulate mass exposure of 3.0 mg/m³. The iron and manganese exposures for the different welding types are also shown in Table II and, in general, follow a similar ranking as total particulate.

To explore the correlations among the different metals, bivariate lognormal distributions were assumed based on the resulting linear ln-ln plots. Figure 1 shows the ln-ln plot of manganese vs. total particulate, while Figures 2 and 3 show similar results for iron and total particulate and manganese and iron, respectively. The correlation coefficient between iron and total mass was the strongest at 0.93, followed by manganese and iron at 0.83 and, finally, by manganese and total mass at 0.80. The metal exposures are highly correlated as one would expect in welding operations. For estimation purposes, the following approximate equations result for the conditional estimate of one metal exposure given another:

$$C_{Fe} = 0.287C_{TP}^{1.16} \quad (1)$$

$$C_{Mn} = 0.018C_{TP}^{1.3} \quad (2)$$

$$C_{Mn} = 0.086C_{Fe} \quad (3)$$

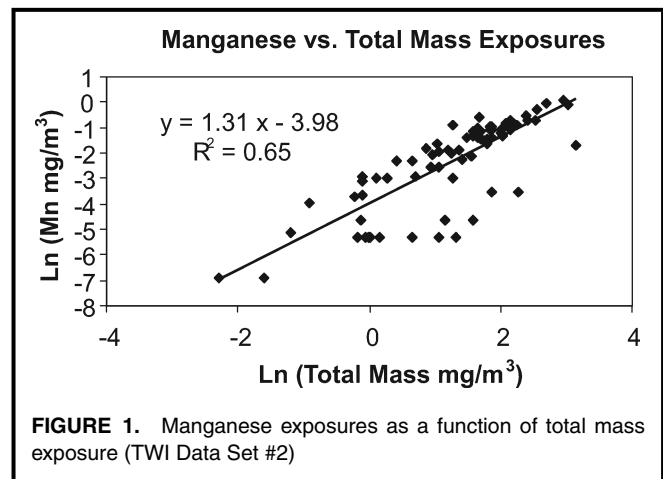


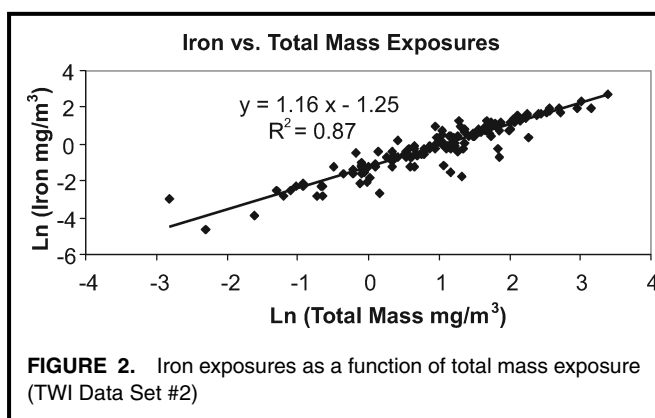
FIGURE 1. Manganese exposures as a function of total mass exposure (TWI Data Set #2)

The TWI data set contains information on the presence of local exhaust ventilation (Yes or No), the location of the personal sampler (behind the helmet, Yes or No), and the degree of confinement for the welding process (A = confined, B = semiconfined or both, and C = other). To explore the impact of these variables on exposures, the TWI Data Set #2 was examined. Table IV summarizes the effects of these variables on exposure. For processes conducted in confined spaces, the total TWA exposure to total mass was 6.83 mg/m³, approximately 82% greater than exposures received in semi-confined spaces (3.76 mg/m³), and more than 2.4 times the exposure levels in other more open areas (2.83 mg/m³).

The presence of local exhaust ventilation was associated with approximately a 35% reduction in total mass exposures (3.01 mg/m³ with LEV vs. 4.61 mg/m³ without) with similar reductions for iron and manganese, which were 41% and 31%, respectively. Finally, the sample location was important for total fume, indicating a reduction of almost 50% when placed behind the helmet vs. in front of it (3.0 mg/m³ vs. 5.9 mg/m³). However, the reduction seen from placement of the sampler behind the helmet for iron was only 23% (1.55 mg/m³ vs. 2.02 mg/m³), and there was no difference in TWAs for manganese (both 0.15 mg/m³).

TABLE III. Total TWA Exposures, Total of Sample Durations (min), and Sample Sizes (N) by Welding Process (TWI Data Set #1)

Welding Process	Total Mass		Iron		Manganese	
	T-min (N)	TWA mg/m ³	T-min (N)	TWA mg/m ³	T-min (N)	TWA mg/m ³
Plasma cutting	132 (1)	67.6	132 (1)	14.0	132 (1)	1.7
MIG/MAG/MMA	19289 (46)	7.1	27309 (48)	2.00	10680 (17)	0.13
FCAW	2590 (23)	7.1	2554 (6)	2.00	3177 (9)	0.20
MIG/MAG	49049 (151)	4.1	47995 (123)	1.85	30701 (80)	0.25
MMA	48109 (205)	3.0	5660 (19)	1.79	4772 (16)	0.17
OXY	3070 (14)	1.8	881 (5)	0.22	674 (3)	0.005
TIG	12035 (51)	1.1	51 (1)	0.08	726 (3)	0.016



A statistical analysis of the total mass exposures was conducted by lumping the confinement Groups A and B into one category (Confined = Yes) and leaving the other Group C as (Confined = No). This helped equalize of the number of samples in each group. A Tukey-Kramer unplanned means comparison was made by testing all eight pairs of means for significant differences; the results are shown in Table V. The test indicates that two pairs of means were significantly different at the $\alpha = 0.05$ level; i.e., confined exposures were significantly greater than unconfined exposures in the absence of local exhaust ventilation regardless of sample location (either behind or in front of the helmet). The same results were obtained for the Tukey-Kramer test using the natural logarithms of the data. The data in Table V show that the highest exposure is in the confined, unventilated case with sampler outside the helmet, while the lowest exposure is the unconfined, ventilated with sampler behind the helmet case. This is consistent with *a priori* expectations. Positioning of the sampler seems to have less impact on exposure with lower exposure levels as may be seen with use of LEV.

CPWR Data Set

Table VI presents an overall summary of exposures by trade in CPWR Data Set #1, including the overall TWA and the average calculated by using the N samples in each trade. The total number of samples (N) and total sampling time in minutes (T) is noted for each trade. The two estimates of the mean

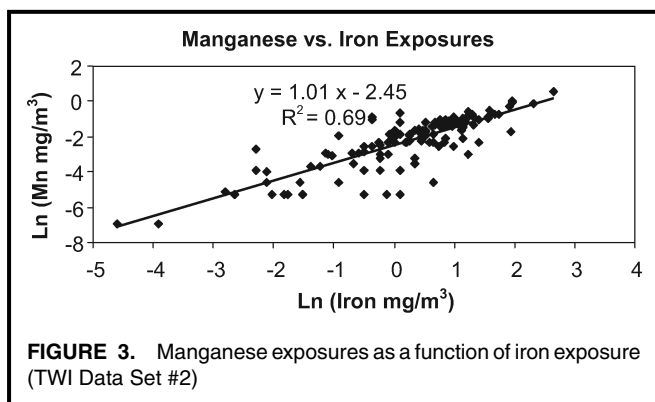


TABLE IV. Summary of Exposures by Confinement Level, Local Exhaust Ventilation, and Sampler Location in TWI Data Set #2

Grouping Variable	Total Mass	Iron	Manganese
	TWA mg/m ³ (N)	TWA mg/m ³ (N)	TWA mg/m ³ (N)
A - confined	6.83 (75)	2.97 (22)	0.20 (11)
B - semiconfined	3.76 (116)	1.33 (10)	0.13 (10)
C - other	2.83 (243)	1.52 (92)	0.13 (49)
LEV = Y	3.0 (229)	1.22 (26)	0.11 (18)
LEV = N	4.61 (205)	2.08 (66)	0.16 (31)
B.H. = Y	3.0 (322)	1.55 (27)	0.15 (22)
B.H. = N	5.9 (112)	2.02 (65)	0.15 (27)

tend to agree best for large sample size and long sampling time. Thus, the means agree well for the pipefitters (N = 137; T = 40806 min) but less so for the boilermakers and pipefitters. The boilermakers had the highest exposures to both manganese (0.26 mg/m³) and total particulate mass (11.79 mg/m³), followed by the ironworkers (0.117 mg/m³ and 7.55 mg/m³) and, finally, the pipefitters (0.077 mg/m³ and 2.89 mg/m³). As in the case of the TWI data, the CPWR samples were of variable duration. The boilermakers had sample times ranging from 70 to 396 min, the pipefitter samples ranged from 64 to 515 min, and the ironworkers samples ranged from 79 to 518 min in duration.

Mean exposures were analyzed using a dichotomous ventilation covariate that indicated the presence of either mechanical and/or local exhaust ventilation (LEV) or simply natural ventilation. The term mechanical ventilation refers to the use of fans and blowers as recirculating and air mixing devices. The results indicate that ventilation was effective for the pipefitters, reducing both total (3.30 mg/m³ vs. 2.61 mg/m³)

TABLE V. Tukey-Kramer Test Results, Total Mass Data from TWI Data Set #2

LEV	Confined	Sampler Behind Helmet?	N	Mean of N (mg/m ³)	Total Time T (min)	TWA (mg/m ³)
N	Y	N	35	10.9*	10713	9.96
N	N	N	47	4.03*	15242	3.87
N	Y	Y	35	4.89**	8400	4.89
N	N	Y	88	2.43**	21776	2.4
Y	Y	N	10	5.73	2013	4.98
Y	N	N	20	3.35	3080	2.61
Y	Y	Y	111	3.28	26640	3.28
Y	N	Y	88	2.56	22093	2.56

Note: * and ** indicate the two pairs of significantly different means ($\alpha = .05$).

TABLE VI. Summary Statistics from the CPWR Data Set by Trade

	Pipefitters		Boilermakers		Ironworkers	
	Manganese (N = 137) T = 40806 (min)	Total (N = 169) T = 51395 (min)	Manganese (N = 48) T = 12119 (min)	Total (N = 51) T = 12894 (min)	Manganese (N = 13) T = 5057 (min)	Total (N = 56) T = 15364 (min)
Total TWA	0.077	2.89	0.26	11.79	0.117	7.55
Sample means	0.077	2.89	0.29	12.36	0.126	7.07
Median	0.04	1.99	0.12	10.82	0.134	5.07
Std. dev.	0.11	2.76	0.39	8.89	0.069	6.51
Minimum	0.0004	0.67	0.006	2.24	0.022	0.62
Maximum	0.74	19.91	1.72	38.73	0.23	40.06

Notes: All measurements are in mg/m³ (T = total time of all samples, in min).

and manganese (0.076 mg/m³ vs. 0.067 mg/m³) exposure by approximately 20% and 12%, respectively. Results were mixed for boilermakers and ironworkers; there was no local exhaust used by these trades, so results are associated with mechanical ventilation only.

Mechanical ventilation consisted of fans and blowers positioned to blow away and/or disperse the fumes. The mechanical ventilation for the ironworkers reduced the exposure to total particulate by about 72% (8.21 mg/m³ vs. 2.3 mg/m³). Boilermakers working at Facility A were continuously welding in a confined space where mechanical ventilation was used as dilution ventilation. In this facility, use of ventilation increased both total (from 8.3 mg/m³ to 13.0 mg/m³) and manganese exposures (from 0.11 mg/m³ to 0.43 mg/m³). However, in Facility H the mechanical ventilation reduced total fume and manganese exposures by 50% (from 8.31 mg/m³ to 4.19 mg/m³) and 74% (from 0.05 mg/m³ to 0.013 mg/m³), respectively.

Since ventilation was used only for welders at Facility A, who were working in a confined space, the work environment was likely the primary factor responsible for the elevated exposures. However, this serves as an important illustration of the limitations of mechanical ventilation for reducing welding fume exposures. Where local exhaust ventilation was used, as was the case with pipefitters, the impact of ventilation was more favorable.

CPWR Data Set #2 was generated to examine the correlation between the manganese and total particulate exposures. Table VII presents a summary of these data by facility. Figures 4 and 5 illustrate the joint distributions of manganese and total particulate for the pipefitters and boilermakers, respectively. In both trades there is a strong correlation ($\rho \sim 0.7$) between the natural logarithms of manganese and total particulate exposures. The least squares regression for the pipefitters suggests an estimator of the form

$$C_{Mn} = 0.015C_{TP}^{1.14} \quad (4)$$

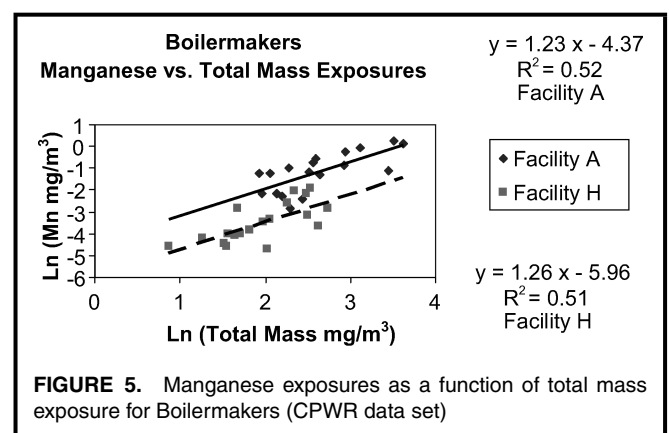
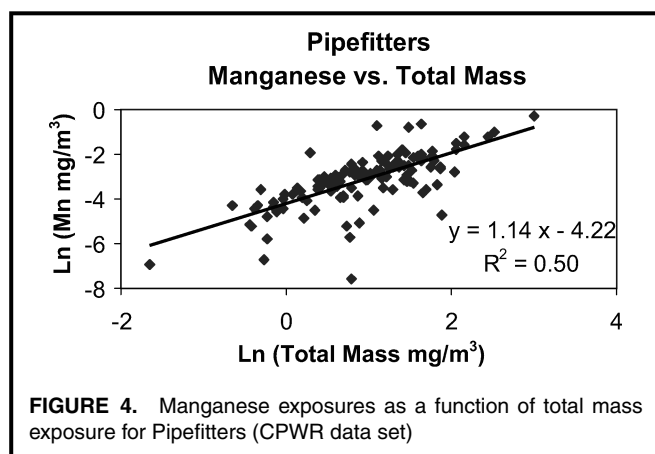


TABLE VII. Summary of the Paired Samples (TP and Mn) from CPWR Data Set #2 by Facility

Facility	Facility Description and Sampling Dates	Workers by Trade and Sample Size (N)	Range – Mn Range – TP Both in mg/m ³	Range – Sample Durations (min)
A	Oil refinery, (rehab/maint) Pennsylvania, March 13–24, 1995	5 BMs N = 18	0.06–1.31 6.93–37.29	145–429
B	Pipe fab shop West Virginia, March 20–30, 1995	4 PFs N = 27	0.011–0.737 0.966–19.905	252–489
C	Oil refinery (underground pipes) Indiana, July 20–28, 1995	9 PFs N = 19	0.0005–0.132 0.73–4.296	64–483
D	Semiconductor Oregon, July 31–Aug 14, 1996	12 PFs N = 20	0.001–0.167 0.193–6.614	257–511
E	Semiconductor California, Sept 9–27, 1996	4 PFs N = 23	0.0034–0.216 0.684–8.644	225–465
F	Pulp and Paper rehab Washington, Oct 29–31, 1996	3 PFs N = 6	0.0059–0.4734 0.518–4.209	389–459
G	Aerospace rehab Washington, Nov 4–7 1996	3 PFs N = 10	0.0012–0.104 0.77–4.58	421–433
H	Power plant; boiler rehab Ohio, April 9–14, 2004	16 BMs N = 19	0.009–0.146 2.37–15.3	120–389
I	New university construction, Michigan 2006	2 PFs N = 16	0.0252–0.3 2.65–11.6	198–430

For the boilermakers, the slopes of the regressions were very close at 1.23 and 1.26, but the intercepts were different by facility. Suggesting approximate equations of the form

$$C_{Mn} = 0.013C_{TP}^{1.25} \quad \text{for work inside oil refinery tanks} \quad (5)$$

and

$$C_{Mn} = 0.003C_{TP}^{0.87} \quad \text{for boiler rehabilitation at electric power plants} \quad (6)$$

OSHA Data Set

The mean manganese exposure from 5339 compliance samples from 1978–early 2008 was 0.266 mg/m³ with a 95% con-

fidence interval of [0.251, 0.28]. Table VIII gives a summary of these data, and Figure 6 shows the annual average as a function of year with the associated 95% confidence interval. There appears to be a fairly stable mean from about 1984 until 2008; however, there is some indication of higher exposures in earlier years. The subset of 504 paired measurements summarized in Table IX shows a mean total particulate exposure of 4.72 mg/m³. Figure 7 shows a log-log plot of the data with an R² of about 0.5 and a least squares regression suggesting an equation of the form:

$$C_{Mn} = 0.04C_{TP}^{0.97}$$

TABLE VIII. OSHA Data Set All Manganese Fume Data

	Mn
Mean	0.27
Median	0.11
Standard deviation	0.55
Count	5339
Maximum	11
Minimum	0.000007
Confidence level for mean (95.0%)	±0.015

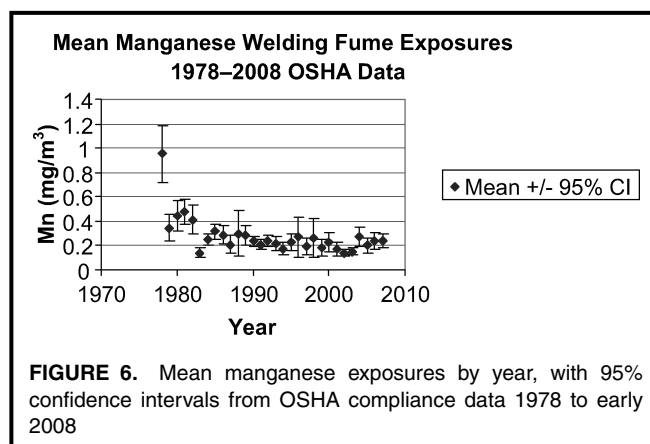


TABLE IX. OSHA Statistical Summary of Paired Data

	Total	Mn
Mean	4.72	0.26
Median	3.12	0.12
Standard deviation	5.74	0.62
Count	504	504
Maximum	60	11
Minimum	0.003	0.0012
Confidence level for mean (95.0%)	±0.50	±0.05

DISCUSSION

Three different data sets are used to examine manganese exposures for a variety of jobs that involve welding to various degrees. The types of welding examined are primarily arc welding in the TWI and CPWR data sets (mostly MMA, MIG, and TIG), while the OSHA data set does not provide any other descriptors to differentiate the type of welding. The data sets have samples of varying time periods, and the data collected are often for different purposes, e.g., compliance, engineering evaluations, exposure assessment, etc. For all these reasons and others, there are questions of comparability. However, despite these limitations there are some interesting and consistent trends in the data.

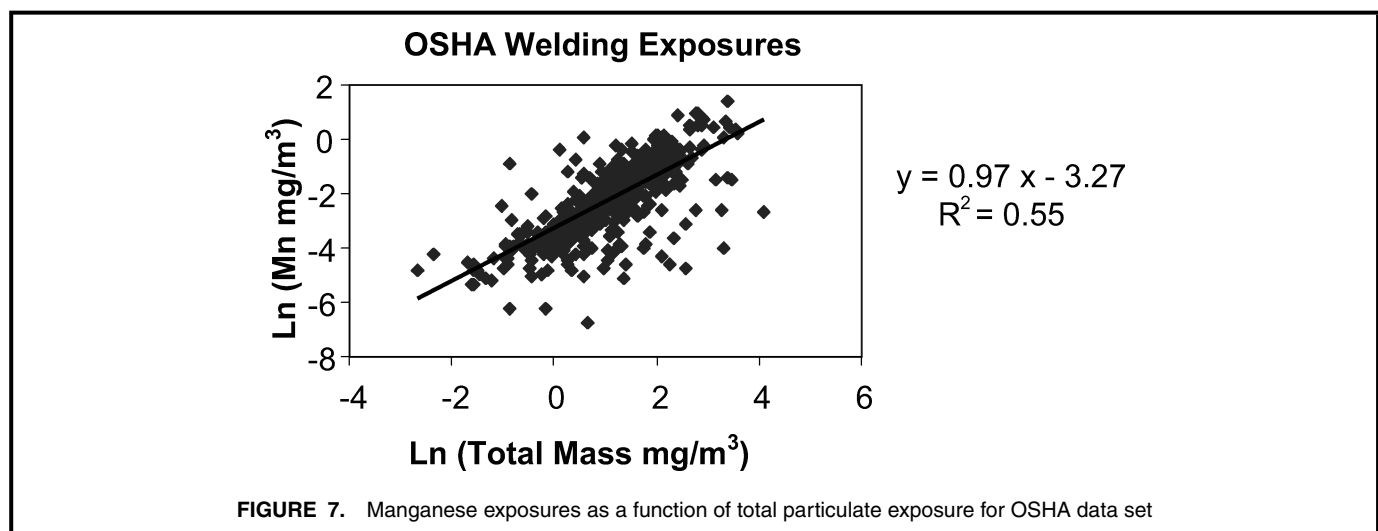
Perhaps the most significant and compelling result is that manganese exposures appear substantial compared with the current ACGIH TLV level of 0.2 mg/m³. The overall mean manganese exposure from the TWI data set is 0.21 mg/m³. For the CPWR data set the boilermakers had a mean manganese exposure of 0.26 mg/m³, the ironworkers had a level of 0.12, and the pipefitters were at 0.08. The mean manganese exposure for welders measured over 20 years by OSHA (over 5000 samples) was 0.27 mg/m³. Mean manganese exposure to arc welders appears consistently over one-half the TLV (the level

commonly used for defining an “action level” relative to an OSHA PEL), and in many cases over the TLV itself.

OSHA sampling is often done by trying to identify the maximally exposed workers rather than using a random sampling strategy. This might be expected to produce a positive bias in the estimated mean exposure. However, OSHA samples are often collected to document that there is not a problem, e.g., in response to complaints. In addition, the possibility that employers may change the work conditions and production parameters to minimize exposures presents the possibility of a counter negative bias. In any case, the OSHA sample results are not based on a random sampling strategy, but that is probably the case for most occupational hygiene measurements.

There is a strong correlation between the exposures to manganese and both total particulate and iron. Correlation coefficients are above 0.7 for all data examined in Figures 1–4, with manganese correlating well with either iron or total particulate levels. This information should be helpful in estimating exposures to manganese when measurements of other fume constituents are available, and for assessing control options. A recent publication⁽³⁵⁾ explores these correlations in more detail using bivariate probability distributions as a mathematical model for mixed exposures.

The TWI data set (Table IV) provided support for the observation that, in general, exposures measured behind the helmet were lower than those measured in front of it for total particulate and iron, even though none of these data were paired. The manganese exposures appeared unaffected by sample location. While a measurement behind the welding helmet is probably a better estimate of true exposure to the welder, from a compliance perspective it is problematic. By measuring behind the helmet, OSHA accords it the status of an approved respiratory device without it having to go through the NIOSH certification process, which establishes the reliability of the protection. With this logic, a face shield could be considered an engineering control for airborne contaminants.



The TWI data indicate the effectiveness of local exhaust ventilation for reducing manganese, iron, and total particulate, as well as increasing levels of exposures associated with increasing degrees of confinement (Table IV). The statistical analysis of these data using the Tukey-Kramer test for multiple mean comparisons presented in Table V suggests a statistically significant elevation in exposures in confined spaces when local exhaust ventilation is absent.

The CPWR data set also provided support for the effectiveness of ventilation, although in this case the results were not consistent and the types of ventilation used were of a mixed nature. Local exhaust ventilation was used only with pipefitters, and, in some cases, mechanical ventilation was used for them as well. For pipefitters, the reductions in total particulate and manganese exposures when local exhaust or mechanical ventilation was used vs. only natural ventilation were reasonably consistent at 21% and 12%, respectively. For the ironworkers, the use of mechanical ventilation vs. natural ventilation resulted in a 72% reduction in total fume exposure; data were not available for manganese comparisons. For the boilermakers, one plant showed a reduction in exposures to both total particulate and manganese, while the other plant did not when mechanical ventilation was used. However, in the latter case, continuous welding with multiple welders was under way in a confined space where ventilation was used.

CONCLUSIONS

The data examined here suggest that arc welding produces manganese exposures that are frequently close to or in excess of the current ACGIH TLV of 0.2 mg/m³. This may present an increased risk of neurological impairment depending on the magnitude and duration of the exposures, the individual's susceptibility, and other factors. The data suggest that local exhaust ventilation can be effective at reducing these exposures, and that in cases where it is not feasible to use it, respiratory protection is needed. When local exhaust ventilation is not in use, welding in confined spaces results in increased exposures to both manganese and total particulate, as mechanical ventilation alone does not seem to be effective.

The data analyzed here and in other studies indicate a strong correlation (consistent Pearson correlation coefficients in excess of 0.7) between the various fume constituents. Iron fume is most strongly correlated with total particulate, but manganese exposures are also strongly correlated with both iron and total particulate. These correlations should be helpful in estimating manganese exposures in cases where only iron or total mass data are available.

Evidence presented here and in other studies indicates that exposures measured behind the helmet are generally lower than those measured external to it. This effect appears to be reduced as overall exposures are reduced and was not observed for the manganese exposures analyzed here. OSHA's compliance policy of sampling behind the helmet is different from all other work operations. PELs are based on breathing zone exposures irrespective of respirator use and are used to

determine the adequacy of the existing engineering controls. OSHA's approach complicates the ability to measure the effectiveness of these engineering controls by introducing the welding helmet as an exposure attenuating device. OSHA should reconsider its existing policy described in the *Field Operations Manual*, which requires compliance officers to sample behind the welding helmet.

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