*Ann. Occup. Hyg.*, Vol. 55, No. 3, pp. 305–318, 2011

doi:10.1093/annhyg/meq088

# Statistical Modeling to Determine Sources of Variability in Exposures to Welding Fumes

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Received 28 May 2010; in final form 1 October 2010; published online 25 February 2011

**Background/Aims: Exposures to total particulate matter (TP) and manganese (Mn) received by workers during welding and allied hot processes were analyzed to assess the sources and magnitudes of variability.**

**Methods: Compilation of data from several countries identified 2065 TP and 697 Mn measurements for analysis. Linear mixed models were used to determine fixed effects due to different countries, industries and trades, process characteristics, and the sampling regimen, and to estimate components of variance within workers (both intraday and interday), between workers (within worksites), and across worksites.**

**Results: The fixed effects explained 55 and 49% of variation in TP and Mn exposures, respectively. The country, industry/trade, type of ventilation, and type of work/welding process were the major factors affecting exposures to both agents. Measurements in the USA were generally higher than those in other countries. Exposure to TP was 67% higher in enclosed spaces and 43% lower with local exhaust ventilation (LEV), was higher among boilermakers and was higher when either a mild-steel base metal or a flux cored consumable was used. Exposure to Mn was 750% higher in enclosed spaces and 67% lower when LEV was present. Air concentrations of Mn were significantly affected by the welding consumables but not by the base metal. Resistance welding produced significantly lower TP and Mn exposures compared to other welding processes. Interestingly, exposures to TP had not changed over the 40 years of observation, while those of Mn showed (non-significant) reductions of 3.6% year$^{-1}$. After controlling for fixed effects, variance components between worksites and between-individual workers within a worksite were reduced by 89 and 57% for TP and 75 and 63% for Mn, respectively. The within-worker variation (sum of intraday and interday variance components) of Mn exposure was three times higher than that of TP exposure. The estimated probabilities of exceeding occupational exposure limits were very high (generally much >10%) for both agents.**

**Conclusions: Welding exposures to TP and Mn vary considerably across the world and across occupational groups. Exposures to both contaminants have been and continue to be unacceptably high in most sectors of industry. Because exposures to the two agents have different sources and characteristics, separate control strategies should be considered to reduce welders' exposures to TP and Mn.**

*Keywords:* determinants of exposure; manganese; mixed-effects models; particulate matter; variance components; welding

## INTRODUCTION

Welders are exposed to metal fumes as well as toxic gases, noise, and ultraviolet and infrared radiation. Welding fumes cause respiratory damage and may also adversely affect dermal, cardiovascular, reproductive and neurological systems (Antonini, 2003; Kim *et al.*, 2005; Antonini *et al.*, 2006; Agency for Toxic Substances and Disease Registry (ATSDR), 2008). The International Agency for Research on Cancer (IARC) classified welding fumes as

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a possible human carcinogen (Group 2B) because of apparent increased risks of lung cancer among welders (International Agency for Research on Cancer, 1990). Because there are roughly 80 welding processes in general industrial use (Burgess, 1995), welders' exposures can potentially be influenced by the type and operation of the process, the composition of welded material and consumables, the work load, the ventilation conditions, etc. Although, many studies have been conducted to examine welding fume exposures and their determinants (Smith, 1967; Pantucek, 1971; Sanderson, 1972; Pantucek, 1975; Kobayashi *et al.*, 1978; American Welding Society, 1979; Ulfvarson and Tech, 1981; Dryson and Rogers, 1991; Castner and Null, 1998; Pires *et al.*, 2006; Flynn and Susi, 2010), none have used sufficiently large datasets to examine exposures from different countries, industries, processes and jobs.

In order to elaborate a more comprehensive picture of welding fume exposure, 2065 air measurements of total particulate matter (TP) and 697 measurements of manganese (Mn) were compiled from international sources. These data were analyzed using a combination of multivariable linear regression models and linear mixed models. We identified important determinants of welding fume exposures while simultaneously estimating variance components of the exposures between worksites, between-workers within worksites, and within-workers over time (both intraday and interday). Finally, the estimated fixed effects and variance components were used to compute the probabilities of exceeding particular occupational exposure limits (OELs).

## METHODS

### *Data compilation*

The scientific literature, mainly in the fields of occupational hygiene and occupational epidemiology, was reviewed to retrieve exposure measurements during welding and allied hot processes (Steel and Sanderson, 1966; Sanderson, 1968; Tola *et al.*, 1977; Goller and Paik, 1985; Dryson and Rogers, 1991; Fairfax, 1994; Barrington *et al.*, 1998; Rappaport *et al.*, 1999; Korczynski, 2000; Wallace *et al.*, 2001; Wallace and Fischbach, 2002; Wurzelbacher *et al.*, 2002). Data were also retrieved from publicly accessible reports from the National Institute for Occupational Safety and Health (NIOSH) (NIOSH Health Hazard Evaluations, 1973–2000). A welding fume database containing exposures in a variety of industrial sectors in Europe and North America was also incorporated (TWI Welding fume exposure database, 2009). (Since the TWI data included some NIOSH Health Hazard Evaluations, redundant data were removed.) Besides welding, measurements from thermal cutting, arc gauging, brazing and burning were included when they were reported. The final data file included 28 sets of data that reported individual exposure measurements. Because a given study often included multiple sampling sites, data were grouped by worksite (51 worksites). Air concentrations reported as lower than the limit of detection (LOD) for TP (0.9%) and Mn (5.3%) were assigned a value of $LOD/\sqrt{2}$ (Hornung and Reed, 1990). If the LOD was not reported, the lowest reported level from the same sampling site was used as a surrogate for the LOD. Along with the exposure measurements, the following details of the sampling regimen and exposure covariates were recorded: experimental or observational study, personal or area sample, sampling duration, country, industrial sector, type of welding process or hot work, base metal, and consumable used. The workplace environment was characterized as being either indoors or outdoors, whether work was conducted in a confined space ($<27\ m^3$ or $1000\ ft^3$) and the type of ventilation.

### *Statistical modeling*

Separate statistical modeling was performed for TP and Mn measurements using the natural logarithm of the air concentration as the dependent variable. We adopted a two-step strategy for building models for these dependent variables. First, we screened all possible fixed effects using the following model:

$$Y_{h(kjl)} = \ln(X_{h(kjl)}) = \beta_0 + \sum_{u=1}^{U} \beta_u C_{u_{h(kjl)}} + e_{h(kjl)}, \qquad (1)$$

for $h = 1, 2, \ldots, H$ worksites; $k = 1, 2, \ldots, K_h$ individual workers at the $h$th worksite; $j = 1, 2, \ldots, J_{h(k)}$ sampling days of the $k$th individual worker at the $h$th worksite; and $l = 1, 2, \ldots, L_{h(kj)}$ measurements on the $j$th sampling day of the $k$th worker at the $h$th worksite, where, $X_{h(kjl)}$ represents the $l$th exposure measurement (TP or Mn) on the $j$th sampling day of the $k$th worker at the $h$th worksite; $Y_{h(kjl)}$ is the natural logarithm of the individual measurement $X_{h(kjl)}$ ($mg\ m^{-3}$); $\beta_0$ is a intercept representing the true underlying global mean (logged) air concentration averaged over all covariate categories; $\sum \beta_u C_{u_{h(kjl)}}$ represents the fixed effects from covariates $C_1$, $C_2, \ldots, C_U$; and $\beta_u$ is the regression coefficient of the $u$th covariate. The exposure covariates were the variables related to process, material, workplace environment, industry, trade, country, study type and sampling regimen (Table 1). The error term $e_{h(kjl)}$ represents the random effect of the $l$th measurement on the $j$th day of the $k$th individual worker at the $h$th worksite. It is assumed that $e_{h(kjl)}$ is normally distributed with means of zero and variances of $\sigma^2_{Y,h}$ (representing the total variance of the logged exposure $Y_{h(kjl)}$). Important fixed effects were selected using Akaike's information criterion (AIC) (Burnham and Anderson, 2002). The relative importance of an exposure covariate $C$ can be estimated by summing the Akaike weights ($w_i$) across all models containing that covariate. The Akaike weight ($w_i$) for a candidate model is defined as

$$w_i = \frac{\exp\left[-\frac{1}{2}(\Delta\text{AIC})_i\right]}{\sum \exp\left[-\frac{1}{2}(\Delta\text{AIC})_i\right]}, \tag{2}$$

where $(\Delta\text{AIC})_i$ is the difference in AIC values between the $i$th model and the model with the smallest AIC value. The larger the value of $w_i$, the more important that covariate becomes relative to others. After selecting main effects, we used the same model to screen for all reasonable two-way interactions.

After screening fixed effects, selected covariates and two-way interactions were fitted by mixed models defined by the following expression (Rappaport and Kupper, 2008):

$$Y_{h(kjl)} = \ln(X_{h(kjl)}) = \beta_0 + \sum_{u=1}^{U} \beta_u C_{u_{h(kjl)}} + b_h + d_{h(k)} + f_{h(kj)} + e_{h(kjl)}, \tag{3}$$

where all common terms are the same as for equation 1. The pre-screened exposure covariates were designated as fixed effects in the model, while the variables for worksite, individual worker, sampling day, and sampling repetition within a day, were designated as random effects. Therefore, the random effects were defined by a four-level nested structure, with variance components across worksites, between workers (within worksites), within-workers across days (interday variability), and within-workers within days (intraday variability). In equation 3, $b_h$ represents the random effect of the $h$th worksite; $d_{h(k)}$ represents the random effect of the $k$th individual worker at the $h$th worksite; $f_{h(kj)}$ represents the random effect of the $j$th day of the $k$th individual worker at the $h$th worksite; and $e_{h(kjl)}$ (error term) represents the random effect of the $l$th measurement on the $j$th day for the $k$th individual worker at the $h$th worksite. It is assumed that $b_h$, $d_{h(k)}$, $f_{h(kj)}$, and $e_{h(kjl)}$ are normally distributed with means of zero and variances of $\sigma^2_{bY,h}$, $\sigma^2_{wY,h}$, $\sigma^2_{wY,k}$ and $\sigma^2_{wY,j}$ [representing the variance components between-worksite, within-worksite and between-worker, within-worker across days (interday), and within-worker within days (intraday)] and that the $b_h$, $d_{h(k)}$, $f_{h(kj)}$, and $e_{h(kjl)}$ are all statistically independent. Thus, $\sigma^2_{Y,h} = \left(\sigma^2_{bY,h} + \sigma^2_{wY,h} + \sigma^2_{wY,k} + \sigma^2_{wY,j}\right)$ is the total variance of the logged exposure $Y_{h(kjl)}$. A compound symmetric variance–covariance structure was used.

We also used a random-effects model with the same four-level nested random effects to examine variance components without controlling for the fixed effects. This model is described as

$$Y_{h(kjl)} = \ln\left(X_{h(kjl)}\right) = \beta_0 + b_h + d_{h(k)} + f_{h(kj)} + e_{h(kjl)}, \tag{4}$$

where the random effects representing worksite, individual worker (within worksite), days, and samples within days are defined as for the mixed model (equation 3). The variance components estimated under equations 3 and 4 were compared to assess the influence of fixed effects on the variance components. Data with missing information on exposure covariates were excluded from the models. All statistical analyses were performed using SAS software for Windows version 9.2 (SAS Institute Inc., Cary, NC, USA).

Finally, we computed two probabilities, namely the exceedance and the probability of overexposure, to assess relationships of TP and Mn exposures to particular OELs (TorneroVelez *et al.*, 1997; Rappaport *et al.*, 1999; Rappaport and Kupper, 2008). The exceedance ($\gamma_h$), defined as the likelihood that a single daily air measurement for a randomly selected worker in the $h$th group on a randomly selected day would exceed an OEL, is given by:

$$\gamma_h = P\{X_{h(ij)} > \text{OEL}\} = 1 - \Phi\left\{\frac{\ln(\text{OEL}) - \mu_{Y,h}}{\sqrt{\sigma^2_{bY,h} + \sigma^2_{wY,h}}}\right\}, \tag{5}$$

where $\Phi\{z\}$ denotes the probability that a standard normal variate would fall below the value $z$ and $\mu_{Y,h}$ is the mean (logged) exposure level for the $h$th group. The probability of overexposure defines the likelihood that a randomly selected worker's (arithmetic) mean exposure in the $h$th group (i.e. $\mu_{x,h(i)}$) would be greater than an OEL and is given by:

$$\theta_h = P\{\mu_{X,h(i)} > \text{OEL}\} = 1 - \Phi\left\{\frac{\ln(\text{OEL}) - \mu_{Y,h} - \frac{\sigma^2_{wY,h}}{2}}{\sqrt{\sigma^2_{bY,h}}}\right\}. \tag{6}$$

Table 1. Exposure covariates examined in the study

| Variable | Type | Values |
|---|---|---|
| Study type | Dichotomous | 0: Observational |
| | | 1: Experimental |
| Air sampling | Dichotomous | 0: Personal |
| | | 1: Area |
| Sampling duration | Dichotomous | 0: Sampling duration $\geq$ 60 min |
| | | 1: Sampling duration $<$ 60 min |
| Year | Continuous | 1966–2005 |
| Country | Nominal | 0: Canada |
| | | 1: Finland |
| | | 2: New Zealand |
| | | 3: UK |
| | | 4: USA |
| Industry | Nominal | 0: Construction |
| | | 1: Manufacturing |
| | | 2: Shipyard |
| | | 3: Railroad |
| | | 4: Automobile |
| Trade | Nominal | 0: Boilermaker |
| | | 1: Iron worker |
| | | 2: Pipe fitter |
| | | 3: Welder fitter |
| Type of work | Nominal | 0: Thermal cutting |
| | | 1: Welding |
| | | 2: Burning |
| | | 3: Brazing |
| | | 4: Arc gouging |
| Ventilation | Nominal | 0: Natural |
| | | 1: Mechanical |
| | | 2: Local exhaust |
| Confined space | Dichotomous | 0: Open space |
| | | 1: Enclosed space ($<$27 $m^3$ or 1000 $ft^3$) |
| Indoor/outdoor | Dichotomous | 0: Outdoor work |
| | | 1: Indoor work |
| Welding process | Nominal | 0: Other (flux cored, submerged, oxy-acetylene welding) |
| | | 1: Shielded metal arc welding |
| | | 2: Gas metal arc welding |
| | | 3. Gas tungsten arc welding |
| | | 4: Resistance welding |
| Base metal | Nominal | 0: Carbon steel |
| | | 1: Mild steel |
| | | 2: High alloy steel |
| | | 3: Aluminum |
| | | 4: Other |

Table 1. *Continued*

| Variable | Type | Values |
|---|---|---|
| Consumable | Nominal | 0: Shield metal arc—carbon low alloy |
| | | 1: Shield metal arc—stainless steel high alloy |
| | | 2: Flux cored arc welding |
| | | 3: Gas metal arc—carbon steel |
| | | 4: Gas metal arc—stainless steel high alloy |
| | | 5: Gas metal arc—Al or Cu |
| | | 6: High manganese |
| | | 7: Submerged arc welding |
| | | 8: Welding with no consumables |
| | | 9: Other |

Estimates of the exceedance and probability of overexposure for the $h$th group, designated $\hat{\gamma}_h$ and $\hat{\theta}_h$, were obtained by substituting estimated parameters into equations 5 and 6, respectively. We estimated exceedances and probabilities of overexposure for different countries and industries based on the parameters estimated under the random-effects model (equation 4). As operative OELs, we used 5 mg m$^{-3}$ for TP, which had been the US Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) until 1992 and the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for total welding fumes prior to 2005, and 0.2 mg m$^{-3}$ for Mn, which has been the ACGIH TLV since 1992.

## RESULTS

### *Descriptive analysis*

The final dataset contained TP and Mn measurements collected in five countries (USA, UK, Canada, Finland, and New Zealand), reflecting exposures in construction, shipbuilding, railroads, manufacturing, and automobile industries from 1966 to 2005. The majority of the data were obtained by personal sampling in observational studies; a few data were collected as area samples (1.3% TP and 4.5% Mn) or from experimental studies of welding parameters (6.2% TP and 9.6% Mn). Welding processes included shielded metal arc welding, gas metal arc welding, gas tungsten arc welding, resistance ,welding and other welding (flux cored arc welding, submerged arc welding, and oxy-acetylene welding). The percentages of measurements below the LOD were 0.9 and 5.3% for TP and Mn, respectively. Repeated measurements accounted for 28% of TP and 48% of Mn measurements (Table 2). The overall arithmetic mean concentrations were 4.79 mg m$^{-3}$ (SD 11.8 mg m$^{-3}$) for TP and 0.502 mg m$^{-3}$ (SD 1.49 mg m$^{-3}$) for Mn. The geometric mean and geometric standard deviation were 1.81 mg m$^{-3}$ and 4.04 for TP and 0.160 mg m$^{-3}$ and 4.54 for Mn. Table 3 presents the summary statistics of TP and Mn data stratified by the exposure covariates. Although only very small portions of the data were from experimental studies or collected as area samples, these reported air concentrations were much higher than those from observational studies or personal samples. A sampling duration $<$60 min resulted in TP and Mn measurements 7-fold higher than when collected over longer time periods. Exposures in enclosed spaces or with only natural ventilation appeared much higher than those in open spaces or with mechanical or local exhaust ventilation (LEV). Although Mn air concentrations were higher indoors, TP concentrations were essentially the same indoors and outdoors.

### *Statistical modeling*

The fixed effects contained in the final models for TP and Mn measurements are presented in Tables 4 and 5, respectively, along with their coefficients and the standard errors (SE) estimated by the mixed effect models (equation 3) and the partial $R^2$ estimated in the multivariate models (equation 1). These fixed effects explained 55 and 49% of the total random variation in TP and Mn measurements, respectively. For TP, 20 and 18% of the total variation were explained by the sampling regimen and industry/trade, while 6% was explained by the process type and material, and exposure in the USA explained 8%. After controlling for other covariates, the mixed model showed

Table 2. Data structure for exposure measurements

| | TP | Mn |
|---|---|---|
| Total measurements | 2065 | 697 |
| Repeat measurements (%) | 571 (28%) | 335 (48%) |
| Total subjects | 1610 | 438 |
| Subjects with repeat measurements | 116 | 76 |
| Subjects with repeat measurements within a day | 58 | 46 |

that TP measurements in experimental studies were significantly higher than those measured in observational studies. Although area samples and samples measured for times <1 h were higher than those measured as personal samples or over longer time periods, these effects were not significant. As indicated by the variable year, TP exposure showed no apparent changes over the examined time period (1966–2005). TP concentrations in the USA were significantly higher than they were in Canada, but there were no differences between Canada and other tested countries. Moreover, the mixed model identified a significant interaction between US and shipyard, indicating a 5-fold higher TP exposure in US shipyards than in other countries (shipyards and other industries). Significant effects of the degree of confinement and ventilation were observed, with TP concentration increasing 67% in enclosed spaces and decreasing 43% with the presence of LEV. Among four different trades, welder fitters had the lowest TP exposure and boilermakers had the highest TP exposure (4-fold higher than for welder fitters). Resistance welding resulted in significantly lower exposure to TP. When welding was performed on mild-steel base metal, TP concentrations were significantly higher compared to welding with other base metals. Use of fluxed-cored and submerged arc welding consumables resulted in slightly increased TP exposures.

For Mn measurements, 17 and 12% of the total variation were explained by the sampling regimen and ventilation, respectively. Industry/trade only explained 6% of the total variation, while the process type and material explained 9%. Regarding the sampling regimen, only sample type had a significant effect, indicating that area samples produced higher air concentrations than personal samples. Unlike for TP exposures, Mn concentrations from observational studies were higher than those from experimental studies after controlling for other fixed effects, and sampling duration had no apparent effect. Exposure to Mn was moderately higher in the USA than in Canada and the UK. However, the strong interaction between US and shipyard indicated that Mn exposure in US shipyards was 20-fold higher than exposures in other countries. Parameter estimates for the variable year indicated that Mn exposure decreased 3.6% year$^{-1}$, but this effect was not significant. Industry and trade appeared to have no significant effects on Mn exposure, except that railroad showed a borderline significant increase on exposure compared to automobile assembly and manufacturing. Among types of work and welding processes, burning and resistance welding produced significantly lower exposures to Mn, and brazing produced significantly higher Mn concentrations compared to welding. As to the influence of materials used, base metal had no apparent effect on Mn exposure. All five consumables in the final model had significant effects. Welding with no consumable or gas metal arc welding with aluminum or copper consumable produced lower exposures; welding with flux cored consumable, high Mn content consumable and gas metal arc welding with carbon steel consumable resulted in higher exposures.

Results from applications of the random-effects models (equation 4) indicated that the between-worksite variance component $\left(\sigma^2_{bY,h}\right)$ produced the greatest percentages of variation for both TP and Mn exposures (53% for TP and 44% for Mn) and that the within-worker variance component reflecting interday variation $\left(\sigma^2_{wY,k}\right)$ produced the smallest percentages of variation for either contaminant (Table 6). The between-worker (within-worksite) variance components $\left(\sigma^2_{wY,h}\right)$ represented 23 and 16% of the total variability for TP and Mn, respectively. The major difference in random-effects models (equation 4) of the two contaminants concerned the within-worker intraday variance component $\left(\sigma^2_{bY,j}\right)$, which represented a larger percentage of the variance of Mn exposure than of TP exposure (36 versus 19%). When the fixed effects were added, the mixed models (equation 3) for TP and Mn exposures showed that the between-worksite variance component $\left(\sigma^2_{bY,h}\right)$ and within-worksite variance component $\left(\sigma^2_{wY,h}\right)$ were reduced substantially, both in absolute value and as percentages of total random variation. In contrast, addition of fixed effects had no discernable effect on the absolute magnitudes of the within-worker interday variance component $\left(\sigma^2_{wY,k}\right)$ or the within-worker intraday variance component $\left(\sigma^2_{wY,j}\right)$. Consequently, under the mixed models, the within-worker variance components contributed proportionally more of the total random variation (i.e. $\sigma^2_{wY,k} + \sigma^2_{wY,j}$=60% of $\sigma^2_{Y,h}$ for TP and 70% of $\sigma^2_{Y,h}$ for Mn) than under the random-effects model (i.e. $\sigma^2_{wY,k} + \sigma^2_{wY,j}$=24% of $\sigma^2_{Y,h}$ for TP and 40% of $\sigma^2_{Y,h}$ for Mn).

The estimated exceedances $(\hat{\gamma}_h)$ and probabilities of overexposure $(\hat{\theta}_h)$ are presented in Table 7 by country and industry. Estimates of exceedances and probabilities of overexposure were large ($>$ 0.10) for all countries, except for TP exposures in the UK, and for all industries, except for TP exposures in the automobile assembly industry. Estimated probabilities were much greater for Mn (OEL = 0.2 mg m$^{-3}$) than for TP exposures (OEL = 5 mg m$^{-3}$). Exposure to Mn in the US had the highest estimated exceedance (35%) and probability of overexposure (51%) of all countries evaluated. Also, the highest probabilities for Mn exposure were observed in the railroad industry, where estimates of the exceedance and the probability of overexposure were 66 and 87%, respectively.

## DISCUSSION

### *Exposure determinants*

These analyses identified several important determinants of exposures to TP and Mn in welding fumes. Air levels of both contaminants were much higher in enclosed spaces and were much lower when LEV was present (Tables 4 and 5). These findings agree with those reported in another recent study that relied largely upon summary statistics and correlation analysis (Flynn and Susi, 2010) (note that some datasets overlapped with those in our study). The welding material also had major effects on exposures. Exposure to TP increased when welding was performed on mild steel or when using consumables for either flux-core-arc welding or submerged arc welding (Table 3). Regarding Mn exposure, consumables with high Mn content profoundly increased air levels of Mn (Table 4). The effect of high Mn content on exposure is also indicated by high Mn concentrations observed in the railroad industry, where steel often has a high Mn content. Among welding processes tested in this study, only resistance welding significantly affected exposures to TP and Mn, in both cases leading to lower air concentrations. The variables industry and trade explained 18% of the total variation in TP exposures (higher in manufacturing and among boilermakers) but only 6% of variation in Mn exposures. Although the variable shipyard did not have a significant main effect on exposure to either agent, a strong interaction was observed between shipyard and US, indicating significantly increased exposures (5-fold for TP and 20-fold for Mn) in the US shipbuilding industry. This interaction effect partially explains why overall exposures in the US were higher than those in other countries. The importance of these sources of exposure is also indicated by the marked reduction in random variation observed when the fixed effects were included in the mixed models, i.e. $\sigma^2_{Y,h}$ was reduced from 2.125 to 0.881 for TP and from 3.906 to 2.189 for Mn (see Table 6). Although some welding processes are thought to have higher fume generation rates than others (American Welding Society, 1979; Burgess, 1995), our results suggest that, in practice, exposures are largely driven by non-welding process factors, such as work-space confinement, ventilation, industry, and trade.

### *Exposure levels*

Symanski *et al.* (1998) investigated long-term exposures to a wide range of airborne contaminants and found clear downward trends in exposures across industries worldwide from 1967 to 1996. The authors reported that 78% of 694 datasets showed linear trends toward lower exposure levels at a median rate of 8% year$^{-1}$ (interquartile range: 4–14%). [A similar range of annual reductions in exposure levels were summarized in a recent review by Creely *et al.* (2007)]. In contrast, our study found no reduction in TP exposure in welding fumes during the time period covered by the compiled data (1966–2005). Exposure to Mn in welding fumes showed a (non-significant) reduction of 3.6% year$^{-1}$, which is equivalent to the lowest quartile of exposure reductions reported by Symanski *et al.* Flynn and Susi (2010) also noted an apparent reduction in Mn exposures among US welders, primarily during years prior to 1984. To determine whether controlling for significant covariates might have obscured significant trends toward reduced TP and Mn exposures, we reran the mixed models without adjusting for ventilation and material (base metal and consumable) and did not find a significant effect of year (results not shown). Simple linear regression models of TP and Mn level on year also detected no significant effects of time on exposure levels (results not shown).

Table 3. Summary statistics for exposures to TP and Mn stratified by exposure covariates, mg m$^{-3}$

| | TP | | | Manganese | | |
|---|---|---|---|---|---|---|
| | *n* | AM | SD | *n* | AM | SD |
| Study type | | | | | | |
| Observational | 1945 | 3.76 | 7.43 | 636 | 0.347 | 0.977 |
| Experimental | 120 | 21.5 | 34.6 | 61 | 2.12 | 3.59 |
| Air sampling | | | | | | |
| Personal | 2038 | 4.26 | 9.69 | 667 | 0.388 | 1.19 |
| Area | 27 | 45.0 | 43.7 | 30 | 3.03 | 3.76 |
| Sampling duration | | | | | | |
| <60 min | 121 | 26.4 | 36.4 | 72 | 2.33 | 3.42 |
| ≥60 min | 1670 | 3.60 | 6.07 | 483 | 0.298 | 0.913 |
| Not specified | 274 | 2.49 | 4.15 | 142 | 0.272 | 0.625 |
| Country | | | | | | |
| Canada | 73 | 2.76 | 3.40 | 115 | 0.236 | 0.556 |
| Finland | 27 | 8.01 | 6.12 | 0 | — | — |
| New Zealand | 18 | 2.32 | 2.36 | 0 | — | — |
| UK | 1204 | 2.41 | 8.54 | 100 | 0.763 | 2.33 |
| US | 743 | 8.78 | 15.4 | 482 | 0.511 | 1.42 |
| Industry | | | | | | |
| Construction | 277 | 5.49 | 6.40 | 198 | 0.132 | 0.233 |
| Manufacturing | 109 | 10.5 | 7.42 | 21 | 0.476 | 0.967 |
| Shipyard | 490 | 3.99 | 10.3 | 28 | 0.839 | 1.16 |
| Railroad | 3 | 7.53 | 6.60 | 21 | 1.42 | 2.02 |
| Automobile | 642 | 1.19 | 1.24 | 66 | 0.0931 | 0.131 |
| Not specified | 544 | 8.24 | 16.6 | 363 | 0.701 | 1.77 |
| Trade | | | | | | |
| Boilermaker | 51 | 12.4 | 8.89 | 48 | 0.291 | 0.392 |
| Iron worker | 57 | 7.07 | 6.51 | 13 | 0.126 | 0.0685 |
| Pipe fitter | 80 | 3.21 | 3.26 | 47 | 0.0928 | 0.145 |
| Welder fitter | 1875 | 4.58 | 12.1 | 588 | 0.561 | 1.62 |
| Ventilation | | | | | | |
| Natural | 792 | 6.60 | 16.0 | 256 | 0.800 | 2.17 |
| Mechanical | 730 | 3.04 | 7.57 | 161 | 0.247 | 0.503 |
| Local exhaust | 406 | 3.58 | 7.34 | 147 | 0.410 | 1.29 |
| Not specified | 137 | 7.24 | 9.88 | 133 | 0.340 | 0.509 |
| Degree of confinement | | | | | | |
| Open space | 1370 | 3.51 | 6.76 | 462 | 0.270 | 0.663 |
| Enclosed space | 387 | 8.15 | 18.7 | 53 | 2.17 | 3.15 |
| Not specified | 308 | 6.23 | 16.2 | 182 | 0.604 | 1.91 |
| Indoor/outdoor | | | | | | |
| Outdoor work | 93 | 4.51 | 3.82 | 97 | 0.291 | 1.03 |
| Indoor work | 1754 | 4.50 | 10.9 | 430 | 0.591 | 1.56 |
| Not specified | 218 | 7.21 | 18.7 | 170 | 0.398 | 1.53 |
| Continuous/intermittent | | | | | | |
| >50% hot work | 233 | 15.5 | 23.7 | 182 | 0.756 | 1.87 |
| ≤50% hot work | 166 | 5.56 | 5.96 | 79 | 0.0644 | 0.0648 |
| Not specified | 1666 | 3.21 | 8.40 | 436 | 0.475 | 1.44 |

Table 3. *Continued*

| | TP | | | Manganese | | |
|---|---|---|---|---|---|---|
| | *n* | AM | SD | *n* | AM | SD |
| Type of work | | | | | | |
| Thermal cutting | 39 | 5.18 | 8.14 | 17 | 0.112 | 0.179 |
| Welding | 1807 | 4.57 | 10.7 | 548 | 0.521 | 1.45 |
| Burning | 5 | 3.85 | 4.73 | 9 | 0.0334 | 0.0309 |
| Brazing | 26 | 2.81 | 2.46 | 12 | 0.0844 | 0.155 |
| Arc gouging | 57 | 5.36 | 6.53 | 19 | 0.449 | 0.745 |
| Not specified | 131 | 7.89 | 23.7 | 92 | 0.571 | 2.06 |
| Welding process | | | | | | |
| Shielded metal arc | 707 | 7.41 | 14.9 | 339 | 0.543 | 1.53 |
| Gas metal arc | 388 | 5.48 | 9.19 | 232 | 0.360 | 0.899 |
| Gas tungsten arc | 109 | 1.04 | 2.14 | 12 | 0.0408 | 0.0389 |
| Resistance welding | 559 | 1.04 | 1.04 | 4 | 0.128 | 0.0126 |
| Other welding | 42 | 2.00 | 2.09 | 17 | 1.66 | 3.20 |
| Allied hot process | 97 | 4.63 | 5.85 | 23 | 0.0901 | 0.140 |
| Non-specified | 163 | 1.60 | 1.47 | 70 | 0.732 | 2.34 |
| Base metal | | | | | | |
| Carbon steel | 173 | 5.43 | 5.50 | 171 | 0.213 | 0.536 |
| Mild steel | 1367 | 4.99 | 11.7 | 411 | 0.610 | 1.61 |
| High alloy steel | 317 | 4.92 | 16.4 | 88 | 0.640 | 2.17 |
| Aluminum | 62 | 2.71 | 3.87 | 10 | 0.124 | 0.217 |
| Not specified | 146 | 2.32 | 3.93 | 17 | 0.309 | 0.460 |
| Consumable | | | | | | |
| Shielded metal arc welding—carbon low alloy | 544 | 5.76 | 10.2 | 243 | 0.249 | 0.694 |
| Shielded metal arc welding—stainless steel | 129 | 11.8 | 25.5 | 23 | 2.75 | 4.30 |
| Flux cored consumable | 96 | 17.5 | 16.8 | 45 | 0.906 | 1.40 |
| Gas metal arc welding—carbon steel | 200 | 3.71 | 3.92 | 157 | 0.423 | 1.36 |
| Gas metal arc welding—stainless steel | 78 | 0.89 | 1.05 | 37 | 0.506 | 1.21 |
| Gas metal arc welding—Al or Cu | 79 | 3.83 | 6.02 | 46 | 0.208 | 0.519 |
| High manganese consumable | 5 | 11.0 | 4.77 | 5 | 2.84 | 1.21 |
| Submerged arc welding consumable | 22 | 1.55 | 1.08 | 0 | – | – |
| No consumable | 725 | 1.85 | 9.74 | 28 | 1.18 | 3.56 |
| Not specified | 187 | 5.43 | 8.72 | 113 | 0.384 | 0.726 |

*n*, samples size; AM, arithmetic mean of measurements.

Moreover, the estimated exceedances and probabilities of overexposure indicated that air concentrations of TP and Mn were unacceptably high, using 5 mg $m^{-3}$ and 0.2 mg $m^{-3}$ as reference OELs for TP and Mn, respectively (Table 6). Indeed, the only estimated exceedance and probability of overexposure found to be $<$10% were for TP exposures in the UK and in the automobile industry. The estimated exceedances and probabilities of overexposure were uniformly high for all countries and industries (no Mn data were available from Finland and New Zealand). In most cases, the probability of overexposure was greater than the corresponding exceedance, which is consistent with earlier findings that when the exceedance is greater than $\sim$0.20, the probability of overexposure tends to be even larger (TorneroVelez *et al.*, 1997; Rappaport and Kupper, 2008). The high probabilities of exceedance estimated in this study are consistent with the findings of Rappaport *et al.* (1999) for both TP and Mn, and of Flynn and Susi (2010) who reported that Mn exposure from welding fumes was frequently at or above the TLV (note that some data sources overlapped with the current study).

The high and generally unacceptable levels of exposure to TP and Mn observed in our study are particularly troubling when considering that welding fumes are known to be harmful to human health. Welding fumes have been classified as a possible human carcinogen by IARC (Group 2B) and a potential occupational carcinogen for lung cancer by the NIOSH (2009). Thus, it is surprising that welding fumes are no longer covered by either an OSHA PEL (since 1992) or an ACGIH TLV (since 2005). The ACGIH provided notice that it intends to lower the Mn TLV from 0.2 to 0.02 mg $m^{-3}$ based on evidence that welders exposed to high levels of Mn experienced neurological effects (ACGIH, 2010). If a new TLV of 0.02 mg $m^{-3}$ were to take effect, our results suggest that it would be exceeded in virtually all welding operations, with exceedances ranging from 56 to 96% and probabilities of overexposure ranging from 79 to 100%.

The high levels of exposure to welding fumes observed in our study are even more troubling in light of the fact that we detected no trend toward reduction in exposure to TP and only a small (non-significant) trend in reduction of exposure to Mn (3.6% $year^{-1}$) in welding operations over the past 40 years. This finding runs counter to the consistent reductions in air levels of most chemical agents (median reduction = 8% $year^{-1}$) that have been well documented over a similar time period (Symanski *et al.*, 1998). Although one can only speculate about the utter

Table 4. Estimated coefficients, SE, *P*-values and partial $R^2$ values for TP measurements ($N$ = 1547)

| Variable | Coefficient estimate (equation 3) | SE (equation 3) | *P*-value (equation 3) | Partial $R^2$ (equation 1) |
|---|---|---|---|---|
| Main effect | | | | |
| Intercept[a] | −0.1013 | 0.4286 | 0.8146 | |
| Experimental study | 1.199 | 0.313 | 0.000 | 0.076 |
| Area sample | 0.710 | 0.528 | 0.181 | 0.083 |
| Sampling duration < 60 min | 0.364 | 0.216 | 0.094 | 0.041 |
| Year | −0.006 | 0.013 | 0.646 | 0.001 |
| US | 0.616 | 0.208 | 0.004 | 0.079 |
| Enclosed space | 0.515 | 0.098 | <0.0001 | 0.015 |
| LEV | −0.555 | 0.096 | <0.0001 | 0.001 |
| Manufacturing | 0.885 | 0.434 | 0.043 | 0.043 |
| Shipyard | 0.292 | 0.377 | 0.440 | 0.046 |
| Trade boilermakers | 1.619 | 0.341 | <0.0001 | 0.050 |
| Trade iron workers | 0.635 | 0.334 | 0.059 | 0.034 |
| Trade pipe fitters | 0.233 | 0.262 | 0.375 | 0.010 |
| Shielded metal arc welding | 0.213 | 0.135 | 0.117 | 0.004 |
| Resistance welding | −0.970 | 0.137 | <0.0001 | 0.005 |
| Other welding (flux cored, submerged, oxy-acetylene) | −0.196 | 0.342 | 0.568 | 0.003 |
| Base metal-mild steel | 0.821 | 0.121 | <0.0001 | 0.047 |
| Consumable-flux cored arc welding | 0.781 | 0.387 | 0.045 | 0.002 |
| Consumable-submerged arc welding | 0.628 | 0.335 | 0.062 | 0.000 |
| Interaction | | | | |
| US* shipyard | 1.660 | 0.723 | 0.023 | 0.007 |
| Enclosed space* US | −0.289 | 0.250 | 0.249 | 0.001 |
| Enclosed space* manufacturing | −0.771 | 0.461 | 0.097 | 0.001 |
| Shielded metal arc welding* base metal-mild steel | −0.214 | 0.175 | 0.223 | 0.001 |
| Other welding* base metal-mild steel | −0.746 | 0.400 | 0.064 | 0.001 |

[a]The intercept represents the estimated log-transformed TP concentration (mg $m^{-3}$) for the combination of observational study, personal sample, sampling duration ≥ 60 min, open space (no >27 $m^3$ or 1000 $ft^3$), natural and mechanical ventilation, country (Canada, UK, Finland, and New Zealand), industry (construction, railroad, and automobile assembly), trade (welder fitter), welding type (gas tungsten and gas metal arc welding), base metal (carbon, aluminum, high alloy steel, and other), and consumable (shielded metal arc welding carbon low alloy/stainless steel, gas metal arc welding carbon steel/stainless steel/Al or Cu, high Mn consumable, and no consumable).

failure to reduce exposures to such well-known health hazards during the last half of the 20th century, it should be clear that something must be done to improve the situation.

*Controlling exposures to welding fumes*

The mixed models developed in this study identified some important determinants of exposures to TP and Mn, particularly the degree of confinement and LEV (Tables 3 and 4). This suggests that particular attention should be paid to controlling exposures in enclosed spaces and implementing improved ventilation practices in welding operations. Other important exposure determinants were different for TP and Mn exposures. The base metal was an important predictor of TP exposure, while consumables were more important to Mn exposure. The variables industry and trade explained 18% of the total random variation in TP exposure (higher in manufacturing and among boilermakers). However, Mn exposure was affected less by industry and trade, which collectively explained only 6% of the variation. These findings indicate that, while focusing upon confined spaces and ventilation will affect both types of exposures, different control strategies may be need to address particular sources of TP and Mn exposures. That is, control strategies that target the industry and type of welding process, which are typically

Table 5. Coefficient estimates, SE, *P*-value and partial $R^2$ for Mn measurements ($N = 515$)

| Variable | Coefficient estimate (equation 3) | SE (equation 3) | *P*-value (equation 3) | Partial $R^2$ (equation 1) |
|---|---|---|---|---|
| Main fixed effect | | | | |
| Intercept[a] | −2.5065 | 0.8401 | 0.0066 | |
| Experimental study | −0.700 | 0.733 | 0.342 | 0.007 |
| Area sample | 1.484 | 0.716 | 0.041 | 0.145 |
| Sampling duration < 60 min | 0.116 | 0.549 | 0.834 | 0.015 |
| Year | −0.037 | 0.023 | 0.116 | 0.019 |
| US | 0.847 | 0.489 | 0.086 | 0.012 |
| Enclosed space | 2.140 | 0.533 | 0.000 | 0.122 |
| LEV | −1.095 | 0.301 | 0.000 | 0.003 |
| Construction | −0.423 | 0.474 | 0.374 | 0.044 |
| Shipyard | 0.998 | 0.956 | 0.298 | 0.000 |
| Railroad | 1.665 | 0.991 | 0.096 | 0.002 |
| Trade boilermakers | 0.806 | 0.606 | 0.187 | 0.008 |
| Trade iron workers | 0.943 | 0.830 | 0.258 | 0.003 |
| Thermal cutting | 0.958 | 0.491 | 0.054 | 0.000 |
| Burning | −1.101 | 0.543 | 0.045 | 0.011 |
| Brazing | 1.767 | 0.762 | 0.022 | 0.003 |
| Arc gouging | 1.707 | 1.537 | 0.269 | 0.009 |
| Resistance welding | −3.730 | 1.160 | 0.002 | 0.004 |
| Consumable-flux cored | 1.433 | 0.466 | 0.003 | 0.007 |
| Consumable-gas metal arc welding Al or Cu | −0.960 | 0.414 | 0.022 | 0.027 |
| Consumable-gas metal arc welding carbon steel | 0.980 | 0.408 | 0.018 | 0.012 |
| Consumable-high manganese | 2.021 | 0.822 | 0.016 | 0.008 |
| Consumable-none | −1.967 | 0.708 | 0.007 | 0.013 |
| Interaction | | | | |
| Enclosed space* construction | −1.630 | 0.883 | 0.068 | 0.011 |
| Enclosed space* shipyard | −2.008 | 1.104 | 0.072 | 0.001 |
| US* shipyard | 2.984 | 1.563 | 0.059 | 0.009 |

[a]The intercept represents the estimated log-transformed Mn concentration (mg $m^{-3}$) for the combination of observational study, personal sample, sampling duration ≥ 60 min, open space (no smaller than 27 $m^3$ or 1000 $ft^3$), natural or mechanical ventilation, Canada and UK, automobile assembly and manufacturing industry, trade (welder fitter), type of work (welding), welding type (gas tungsten arc welding, gas metal arc welding, shield metal arc welding, other welding, and allied hot process), and consumable (shielded metal arc welding, gas metal arc welding—stainless steel, and submerged welding).

Table 6. Variance component estimates for the one-way random-effects (equation 4) and mixed-effects models (equation 3) for TP and Mn exposures

| Variance component | TP exposure | | Mn exposure | |
|---|---|---|---|---|
| | Random-effects model (equation 4) | Mixed-effects model (equation 3) | Random-effects model (equation 4) | Mixed-effects model (equation 3) |
| Between worksite $\left(\sigma^2_{bY,h}\right)$ | 1.124 (53%) | 0.119 (14%) | 1.744 (44%) | 0.434 (20%) |
| Between-worker within-worksite $\left(\sigma^2_{wY,h}\right)$ | 0.494 (23%) | 0.214 (24%) | 0.622 (16%) | 0.227 (10%) |
| Within-worker interday $\left(\sigma^2_{wY,k}\right)$ | 0.107 (5%) | 0.162 (18%) | 0.145 (4%) | 0.131 (6%) |
| Within-worker intraday $\left(\sigma^2_{wY,j}\right)$ | 0.400 (19%) | 0.386 (44%) | 1.396 (36%) | 1.397 (64%) |
| Total $\left(\sigma^2_{Y,h}\right)$ | 2.125 | 0.881 | 3.906 | 2.189 |

Table 7. Estimated parameters, exceedances, and probabilities of overexposure for exposures to TP and manganese (Mn) for different categories of exposure

| Variable | Group mean (logged data) $\hat{\mu}_{Y,h}$ | Group mean (natural scale data) $\hat{\mu}_{X,h}$ | Between-group variance component $\hat{\sigma}^2_{bY,h}$ | Within-group variance component $\hat{\sigma}^2_{wY,h}$ | OEL (mg m$^{-3}$) | Exceedance $(\hat{\gamma}_h)$ | Probability of overexposure $(\hat{\theta}_h)$ |
|---|---|---|---|---|---|---|---|
| TP | | | | | | | |
| US | 1.137 | 6.488 | 1.001 | 0.465 | 5 | 0.348 | 0.405 |
| UK | −0.069 | 1.943 | 1.001 | 0.465 | 5 | 0.083 | 0.074 |
| Canada | 0.438 | 3.224 | 1.001 | 0.465 | 5 | 0.167 | 0.174 |
| Finland | 2.000 | 15.380 | 1.001 | 0.465 | 5 | 0.626 | 0.733 |
| Manufacturing | 1.433 | 8.726 | 1.003 | 0.464 | 5 | 0.442 | 0.522 |
| Construction | 1.252 | 7.285 | 1.003 | 0.464 | 5 | 0.384 | 0.450 |
| Railroad | 1.490 | 9.242 | 1.003 | 0.464 | 5 | 0.461 | 0.545 |
| Shipyard | 0.123 | 2.354 | 1.003 | 0.464 | 5 | 0.110 | 0.105 |
| Automobile | −0.237 | 1.644 | 1.003 | 0.464 | 5 | 0.064 | 0.054 |
| Non-specific | 0.832 | 4.788 | 1.003 | 0.464 | 5 | 0.261 | 0.293 |
| Mn | | | | | | | |
| US | −2.324 | 0.525 | 1.892 | 1.467 | 0.2 | 0.348 | 0.506 |
| UK | −3.421 | 0.175 | 1.892 | 1.467 | 0.2 | 0.162 | 0.217 |
| Canada | −2.618 | 0.391 | 1.892 | 1.467 | 0.2 | 0.291 | 0.421 |
| Manufacturing | −2.377 | 0.453 | 1.674 | 1.495 | 0.2 | 0.333 | 0.494 |
| Construction | −3.202 | 0.198 | 1.674 | 1.495 | 0.2 | 0.185 | 0.257 |
| Railroad | −0.884 | 2.016 | 1.674 | 1.495 | 0.2 | 0.658 | 0.873 |
| Shipyard | −2.074 | 0.613 | 1.674 | 1.495 | 0.2 | 0.397 | 0.587 |
| Automobile | −3.629 | 0.130 | 1.674 | 1.495 | 0.2 | 0.128 | 0.163 |
| Non-specific | −2.251 | 0.513 | 1.674 | 1.495 | 0.2 | 0.359 | 0.533 |

$\hat{\mu}_{Y,h}$, estimated group mean for logged data, obtained from application of random-effects model (equation 4) to the logged concentrations (mg m$^{-3}$) grouped by country and industry; $\hat{\mu}_{X,h}$, estimated group mean for natural scale data (mg m$^{-3}$); $\hat{\sigma}^2_{bY,h}$, between-group variance component, estimated from application of the random-effects model (equation 4) to the logged concentrations (mg m$^{-3}$) grouped by country and industry; $\hat{\sigma}^2_{wY,h}$, within-group variance component, estimated from application of the random-effects model (equation 4) to the logged concentrations (mg m$^{-3}$) grouped by country and industry.

used for controlling TP exposures, may not be as effective for reducing exposures to Mn, where the type and composition of welding consumables should be a major target for controls. Moreover, we observed that within-worker variation in Mn exposure was three times larger than that in TP exposure, indicating great intraday and interday variability in Mn exposure for a given welder. While between-worker variability calls for individual-level controls to reduce exposure levels for highly exposed workers (investigating personal environments including location, types of equipment, and specialized work activities), within-worker variability is more likely to result from environmental variables, including shared tasks (such as performing different types of welding during a day or on different days), that affect all welders and thus require administrative and engineering solutions (Rappaport and Kupper, 2008).

**FUNDING**

The database for this investigation was compiled with partial support (to S.M.R.) from grant U54OH00830 of the NIOSH (via the Center to Protect Workers Rights, CPWR). Work was performed with partial support from a contract (to S.K.H) jointly from the management of an automobile assembly facility and United Auto Workers, as well as from grant T42 OH 008429 of the Northern California NIOSH Education and Research Center (to S.L.).

*Acknowledgements*—The authors appreciate the contributions to the primary data generated by the CPWR and its contractors as well as the cited Health Hazard Evaluations of NIOSH and the online database produced by TWI. We also appreciate the cooperation of the thousands of workers who permitted their exposures to be measured.

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