STANDARDS RESEARCH

Quantitative Assessment of Metals and Particulates Exposure in Women and Men in the Welding Trades

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Executive Summary

This project extends work on the Women's Health in Apprenticeship Trades—Metalworkers and Electricians (What-me) project, a prospective cohort of women welders from across Canada, set up in 2010 by a research team from the University of Alberta at the request of the CSA W117.2 Technical Committee on safety in welding, cutting, and allied processes. The primary objective of the What-me project was to examine the effects on the fetus when welding during pregnancy and, secondarily, the effects on the health of the welders themselves.

The project extension reported here was put in place to provide quantitative, validated estimates of exposures to particulates and metals during welding that could be used, in a second step, to evaluate levels of exposure associated with any observed adverse health outcomes in the What-me project. This report describes the methods and results of three stages in the estimates of exposure, (1) the literature search, extraction, and statistical modelling of published data from 179 articles producing a total of 2,965 summary statistics; (2) the collection and analysis of exposure data from 60 experimental welding sessions carried out in the Canadian Centre for Welding and Joining at the University of Alberta; and (3) the validation and calibration of statistical models using data from both sources.

The resulting statistical models, presented here for total particulates, provide a tool for quantification of exposures within the What-me project. They will also be of use to other researchers and practitioners who have access to process description without the capacity for direct measurement of airborne exposures.

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Introduction

This project extends work on the Women's Health in Apprenticeship Trade—Metalworkers and Electricians (What-me) project [1], a prospective cohort of women welders from across Canada, set up in 2010 by a research team from the University of Alberta at the request of the CSA W117.2 Technical Committee on safety in welding, cutting, and allied processes. The primary objective of the What-me project was to examine the effects on the fetus when welding during pregnancy and, secondarily, the effects on the health of the welders themselves. To meet this second objective, the women's cohort was supplemented by a cohort of male welders (What-men) from Alberta. The work was carried out by a team from the Division of Preventive Medicine at the University of Alberta. A total of 1,001 welders, including 447 women, joined the cohorts. Data collection for the main study was completed in 2018 and the data are being extensively analyzed.

During the analysis conducted by the University of Alberta research team, it was determined that there was a need to collect new data on workplace exposure to metals and particulates. Statistical models of exposures of women and men within the cohort have been developed, but these needed to be validated against external data. The validation of the exposure models would then enable the research team to confidently use the models to analyze the impacts of exposure levels on pregnancy outcomes in female welders, and on their respiratory and dermal health.

The main objective of this current project as described in this report was to *validate exposure estimates by conducting ambient air sampling and analysis.* It was anticipated that ambient air monitoring of welding activities, classified by type, base metal, and consumables, would provide objective validation of the exposure estimates, resulting in a publishable report on the development and validation of the exposure algorithms. The algorithms will be used to provide quantitative estimates of the effects of welding exposure on pregnancy outcomes and health effects (dermatitis, asthma) that may be related to welding fumes being inhaled by both women and men in the welding trades.

1. Background

1.1 The What-me Study

The What-me study was designed to examine welding exposures and their effect on the unborn child. Data collection began in 2011 with the creation of a cohort of women welders. In 2013, a male version of the cohort (What-men) was also established to study health outcomes associated with work in the trades. Both cohorts included participants from the welding and electrical trades. What-me was comprised of women from across Canada, while the men's cohort was limited to participants from Alberta. The welding trades included 1,001 participants, 447 women and 554 men, while the electrical trades represented a total of 885 participants, 438 women and 447 men. Participants were asked to complete a baseline questionnaire that collected demographic information, a complete job history since leaving high school, and information on eight health conditions, infertility, and, for women, all pregnancies. A follow-up was completed approximately six months after the baseline questionnaire and every six months thereafter. Women were followed for up to five years and men for up to three years.

The welder follow-up questionnaires provided updated information on health and pregnancy but also, importantly for this project, included a series of questions about work in welding. These included all jobs since the last questionnaire, all job tasks performed in their most recent job, and a detailed, trade-specific set of subroutines associated with tasks in the welding trades. These detailed subroutines were divided by welding processes: manual metal arc welding, semi-automatic arc welding, arc welding with tungsten electrode, plasma arc welding, and submerged arc welding. Other subroutines were included in the questionnaire but are not examined here. The welding process subroutines contained questions about the welding consumables used, such as rods/filler metals together with shielding gases and fluxes. Further questions pertained to the base metals welded, surface coatings, ventilation, confined space, and respiratory equipment (Appendix A).

The welding subroutines were developed, in part, because the wide geographic scope of the study made it impossible to monitor the day-to-day welding exposures in the participants' workplaces. It was instead necessary to estimate these exposures through the detailed task questionnaire and to validate these exposure estimates. In order to do this, with funding from the CSA Group, the most common scenarios encountered in the study were replicated and their fumes measured. This process is described below.

1.2 Welding Processes

Welding processes comprise five main categories, with three covering most welding activities in Canada. These are manual metal arc welding (MMAW), semi-automatic arc welding (referred to as flux-cored arc welding [FCAW], gas metal arc welding [GMAW], and metal-cored arc welding [MCAW]), and arc welding with tungsten electrode (often referred to as gas tungsten arc welding [GTAW]). Two other less commonly seen categories are submerged-arc welding (SAW) and plasma arc welding (PAW) [2]. There are also different base metals that are selected to satisfy various properties and could broadly be described as low alloy steels, high alloy steels (a very unspecific term), and aluminum. These base metals are the most commonly seen in the industry, but mild steel and galvanized steel are the main low alloy steels of interest here, while the main high alloy steel of interest for this study is stainless steel (with higher chromium and nickel content). These base metals are generally used with a welding rod or filler metal that both matches the steels being welded and the desired welding properties. A variety of fluxes and shielding gases (often argon, carbon dioxide, or combinations of both) can also be used to create a micro atmosphere, which protects the weld from outside elements during the arc activity.

Certain metals commonly found in base metals or consumables may carry a risk to a worker's health. Chromium (Cr) and hexavalent chromium (Cr^6) have been associated with work-related skin problems, lung cancer, and fertility issues [3]–[6], while zinc has been associated with metal fume fever, nickel with lung cancer, and manganese and aluminum potentially with diseases of the nervous system [4]. During welding activities, these metals can take different forms and become airborne ultrafine particles, which are able to penetrate the lungs and lung tissues and enter the blood stream, making welders vulnerable to ill-health. A significant proportion of the deposited respirable particles (< 10 µm), ranging from 10- to 50% in the case of manganese for mild-steel welders to 90% of the deposited respirable Cr in the case of stainless steel welders, has been observed to be of a nanoparticle size (< 300 nm) [7]. These exposures are not trivial and, if adequate safety measures are not taken, can seriously harm the exposed workers.

1.3 Exposure Matrices

Previous authors have attempted to construct welding exposure matrices to describe how exposures vary with different welding scenarios. However, few have successfully examined the relationship between specific welding exposures and health outcomes, and none have done so specifically for pregnancy outcomes. Currently, the best welding exposure matrices only include welding process and base metal and sometimes include other features like year of sampling or the sampler used. None comprehensively includes welding process, base metal, and rod/filler metal [8]–[13]. This posed a problem in that it was of interest for this study to examine all three factors and how they affected exposures in the What-me and What-men welders. Furthermore, no welding exposure matrix from the literature included all of the scenarios that were most common in the What-me and What-men studies.

1.4 Objective

The objective of the project was to develop, and validate, a welding occupational exposure matrix to estimate exposure to particulates and metals through fumes or dust that were directly relevant to the exposures of the welders in the What-me and What-men studies. The scenarios included welding process, base metal, and consumable. The approach taken was to:

1. **Gather usable exposure data from the literature to produce a mathematical exposure model.**
2. **Collect data through controlled (experimental) scenarios on welding fumes for specific combinations of welding process, base metal, and consumable to better describe exposures and, as a second step, to validate the mathematical model produced from the literature.**
3. **Use these experimental data to calibrate the existing model and produce a final exposure model from which exposures can be estimated for the entire cohort.**

In subsequent work, these exposure estimates will be used to assess the effect of welding exposures on health outcomes, including pregnancy. This report will focus on total dust as the primary outcome of interest.

2. Methods

2.1 Systematic Review

2.1.1 Literature Search and Data Extraction

A systematic review on occupational welding exposures was conducted in 2016 and revisited in 2019 to gather more recently published articles. Search terms were selected that would enable us to identify the most relevant articles for this literature review. Only articles published in English or French in peer-reviewed journals were included. The terms used in the search were *exposure, welding, and metal,* and they were run in three databases: MEDLINE (PubMed), Web of Science, and CINAHL. The terms were searched together and produced a total of 1,844 articles in 2016 and 309 in 2019. Duplicates were removed and all titles and abstracts were downloaded for further scrutiny. A total of 413 articles were reviewed and considered for the data extraction by two independent reviewers and identified as either containing useful information on welding exposures (air concentrations) or not. At that stage, any article that had not received a unanimous decision on whether or not to include it in the data extraction stage was included so as to not pre-emptively remove potentially relevant articles. The next stage was to read the articles and extract the data where applicable or to make the decision to discard the article. Any discrepancies in the decision to keep the article or not were reviewed by a third researcher and a final decision was made. Finally, data was extracted from 179 articles.

The data extracted were particulate concentrations shown either as total dust, inhalable dust, respirable dust, or presented as specific metal concentrations. Data on the sampling procedures were gathered, such as the number of hours sampled, personal sampling versus area sampling, whole shift sampling versus grab sampling, number of sites visited, and year and country of sampling, along with industry where the sampling took place. All summary statistics given in each article were gathered. These statistics were any of the following: means with standard deviations, geometric means and

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geometric standard deviations, medians, interquartile or numeric ranges. These data were then cross-checked between the two reviewers and any discrepancy in the data was then verified in the original articles. Along with information on the sampling itself and on occupation, data were gathered on welding processes, base metals, rods or filler metals, confined spaces and the use of ventilation, coatings, and shielding gases (see extraction sheet in Appendix B). In total, this process yielded data from 179 articles, producing a total of 2,965 summary statistics from which to narrow down the search to more specific features of the sampling and welding.

2.1.2 Statistical Analysis of Data Extracted from the Literature

Most environmental or occupational hygiene samplings will yield positively skewed results, and it is generally better to analyze data that are geometric means along with their geometric standard deviations [14], [15] than other summary statistics. However, in this case, the vast majority (71%) of summary statistics were given in arithmetic means (SD) and it was decided that it was better to estimate fewer values through various methods than to estimate the majority of them by forcing an analysis of geometric means. Arithmetic means were then log transformed before the modelling began, as seen in the Aidoo *et al.* study [16]. The modelling was done in Stata 15.1 using a mixed linear regression, adjusting for the effects of heterogeneity between articles by including a random effect representing the article from which data were extracted. The analysis used frequency weights. The analysis of total dust was narrowed down to a single, known process only but base metals and consumables were permitted to be unknown so that, at minimum, the effect of the process would be measured. The analysis was restricted to whole shift samples, which were defined in the literature as either shift samples or samples that were at least 2.5 hours in length. Further, the analysis was restricted to personal samples.

2.2 Air Sampling of Exposures in the Experimental Welding Scenarios

Before replicating the most common welding scenarios in the What-me and What-men studies, it was necessary to identify them to maximize the number of participants for whom exposures could be estimated. To do this, many questionnaires had to be scrutinized such that clear answers on each of the items in the exposure matrix (welding process, base metal and consumable) could be obtained. When a rod or filler metal was unknown or unclear, the participant was assigned the most common consumable, which was predetermined by a welding expert employed to do so. The base metal and welding process, for the most part, were not estimated simply because participants almost always remembered these. Table 1 shows the most common scenarios that were replicated in a controlled setting with their corresponding mean total dust concentrations.

Samples were collected on 37 different days during the summer of 2019. The welding sessions took place in the Canadian Centre for Welding and Joining at the University of Alberta using the same GMAW, GTAW, or MMAW for the vast majority of samples. The aluminum GMAW was performed using a machine provided to the research team by the Northern Alberta Institute of Technology (NAIT) because it had a spool gun attachment that was needed to complete the aluminum welding scenarios. On some days only one welding session was completed, while on other days two sessions were completed, and on one occasion three sessions were completed. On days with more than one welding session, each session was separated by a period of one hour of high-flow ventilation to ensure that the second sample would not be contaminated by the particles from the first sample. Additionally, in order to ensure that first sessions were not systematically different from second sessions, scenarios were partially quasi-randomized such that each scenario would not only be completed as a first session or as a second session (or third). The same welder was used for all sessions wearing the sampling cassette in the same location each time. The welder was equipped with protective clothing, gloves, a welding helmet, and wore a P100 mask for every session. The welder was also accompanied by a welding buddy who was there to ensure the welder's safety and the proper functioning of the sampling equipment.

The welding/sampling time was, on average, 178 minutes (median 180). Three hours was chosen because it would provide sufficient sampling material to obtain a full metals analysis along with a total dust estimate for each scenario. The base metals used were of the same classification for all of the welding scenarios, and the consumables came from the same manufacturer within that scenario. All mild steel scenarios (including galvanized steel) were performed with A36 mild steel, the stainless steel scenarios were performed on 304 stainless steel, and the aluminum was 5052 classification. All metals were purchased at the same location from a single provider, ensuring that they were indeed the correct classification. Consumables were purchased mainly from one source but some were donated from NAIT and one spool was donated from Lincoln Electric. The mild steel GMAW and MCAW scenarios were accompanied with a mix of carbon dioxide and argon gas (75/25%), while the GTAW sessions were all performed with 100% argon. The GMAW stainless steel and aluminum sessions were both performed with 100% argon gas. FCAW was performed gasless. For MMAW, rods of the same size (1/8″) were used across scenarios in an attempt to reduce confounding by the amount of consumable used. For the GMAW, FCAW, and MCAW welding sessions, 0.035″ filler wire size was used for all of the metals, and for GTAW welding, 3/32″ was used. Table 2 shows the mean concentrations by each welding scenario factor separately.

2.3 Weighing and Metals Analysis Procedures

Before each welding session, 5 μm PVC filters (37 mm diameter) were carefully treated for static control, then weighed and their weight recorded. The filters were mounted in a clean total dust cassette and both sides of the cassette were sealed until the welding session began [17]. Using a flow rater, the sampling pumps were calibrated before and after each welding session. At the beginning of each welding session, the cassette was connected to a Gilian Plus personal air sampling pump (Sensidyne®, St. Petersburg, Florida, USA). After each sampling session, the cassette was again sealed, brought back to the laboratory, and stored in a desiccator for at least two days before the filters were removed from the cassette and weighed. The weighing procedure again included a static control procedure, followed by weighing on the scale according to NIOSH method 0500 [18]. Five field blanks were also taken to check for procedural error, and these were used to derive a limit of detection.

For the metals analysis, filter digestion was performed at the Soil, Water, Air, Manure, and Plants (SWAMP) laboratory at the University of Alberta. All preparation procedures were carried out in Class 100 metal-free air cabinets. Filter samples were digested in a high-pressure microwave (Ultraclave, Milestone®, Leutkirch, Germany) using a mixture of 3 ml nitric acid and 0.1 ml of tetrafluoroboric acid (HBF_4) following NIOSH method 7304 [19]. All acids were sub-boiled and plasticware was acid-cleaned prior to use to avoid any metal contamination during sample preparation and analysis. Samples were completed to 10 ml and diluted 10-fold for field blanks and ambient air samples and 100-fold for welding fume samples. Analysis was performed on an iCAP-Q Inductively Coupled Plasma Mass Spectrometry (ICP/MS) (Thermo-Finnigan®, Bremen, Germany).

3. Results for Total Particulates

3.1 Systematic Review Model

The final numbers from the systematic review included 42 articles, which gave a total of 152 means representing a total of 3,636 total particulate or respirable fraction samples. Table 3 shows the weighted mean concentrations stratified by each of the factors that contributed to the model. It was decided that respirable fractions and total particulate samples would be analyzed together, provided that a factor be included that identified the two groups. The most particulate-producing process in the systematic review was FCAW, while the most particulate-producing metal was mild steel. The consumable producing the most suspended particles was E71T1, and the observed total particulates, before logarithmic transformation, were about 38% higher than the respirable fraction.

In a frequency weighted univariate mixed linear regression with GTAW as the reference category, FCAW remained the highest particle-producing welding process, while MMAW and GMAW exchanged positions such that GMAW had a higher mean concentration than MMAW (Table 4). Both of these were significantly higher than GTAW. This resembles the results found in the study by Lehnert *et al.* [11] which compared the same welding processes in a large study using data from the MEGA database in Germany.

In a univariate regression, including only base metal and with aluminum as the reference category, it was found that the highest concentration was with mild steel, while stainless steel and high alloyed steel both produced the lowest concentrations. For consumables, the reference category in the univariate model was the category for unknown/multiple so that it would make explicit the effect that consumables have on exposures. E71T1 produced the highest exposure, as visible in Table 3, and was significantly higher than the unknown/multiple group. What was notable in Table 4 was that ER308, ER309, TECH276, and FC308 showed significantly lower concentrations than the unknown category. The factor representing respirable dust showed a reduction in particulate matter, but this was not significant in a univariate model.

The multivariate model from the systematic review can be seen in Table 5. The same reference categories were used as in the univariate models and results were relatively similar to the univariate ones. It was found that the processes were largely unchanged and that all processes were significantly higher than GTAW. Metals, however, were greatly affected by the multivariate nature of the model. All metals showed significantly higher concentrations than aluminum, including the unknown/multiple category. What can be observed for consumables is that the only significantly different consumables from the unknown category are those that show a reduction in concentration of total dust (E309, E7018, ER308, ER309, TECH276, FC308). Four of these were stainless steel consumables, one high alloyed steel and the other a mild steel consumable.

3.2 Results of the Experimental Scenario Replication

A total of 61 welding sessions were undertaken representing 21 scenarios. The mean concentrations are shown in Table 1 by scenario and in Table 2 by welding process, base metal, and consumable. One sample was not included in this analysis because it had been contaminated. Much like in the systematic review data, the process producing the highest concentrations of particulate matter was FCAW, followed by MCAW (not included in the systematic review) and GMAW, with GTAW producing the smallest amounts of particles. Mild steel was the highest emitting group, followed by galvanized steel and stainless steel. In the experiments, aluminum showed the lowest particulate concentration of all the metals, which is somewhat different from the literature. For consumables, E71T1 showed the highest concentrations, immediately followed by ER70S6, E70C6M, and E6010. The highest-producing consumables were all mild steel consumables, while the lowest ones were aluminum and stainless steel. Another observation that was made was that the total particulate

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concentrations were much higher than those observed in the literature; this will be discussed later. Overall, a visual inspection of Table 2 and Table 3 shows us that there was some degree of agreement between the experiment and the literature on welding process, base metal, and consumable.

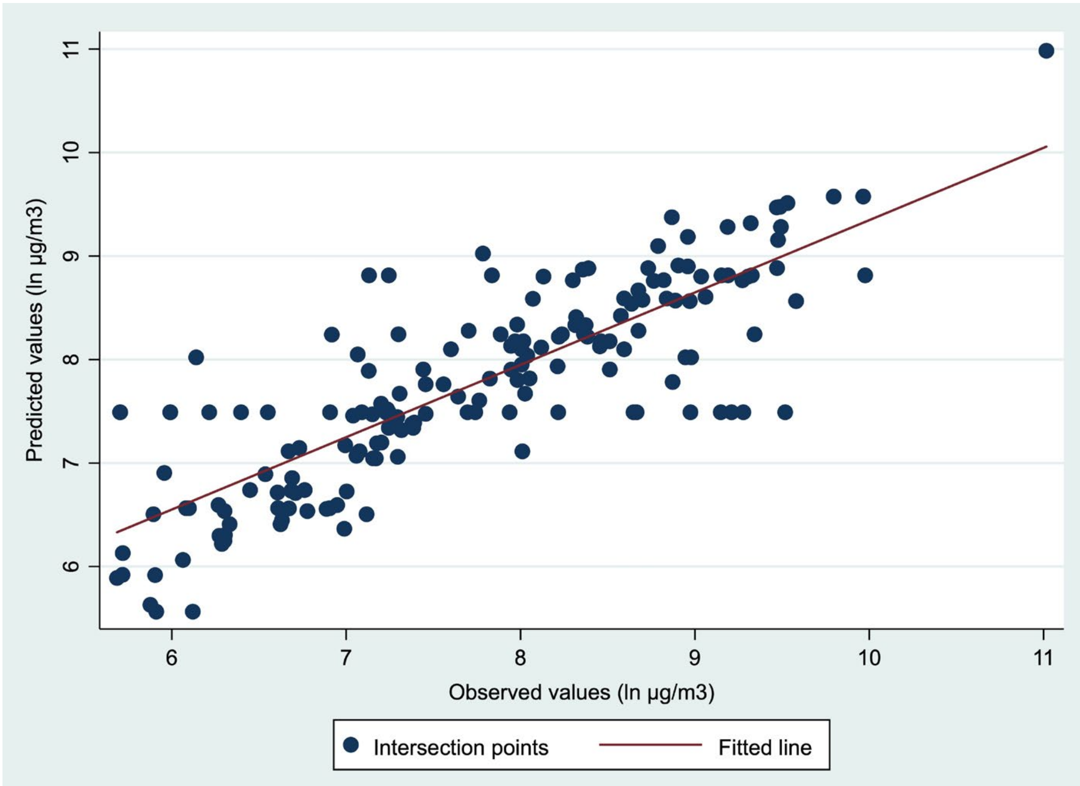
3.3 Validation

The purpose of this study was to estimate exposures for the What-me and What-men cohorts. Therefore, it is important to both examine the predicted values modelled from the systematic review and compare those to the measurements taken in the scenario replication, and to compare the relative rank of the predicted values against the observed values from the experiment. First, an examination was performed of whether the values obtained from the experiment fit within their predicted confidence intervals from the systematic review model. To do that, because of the various welding processes, base metals, and consumables from the What-me welding scenarios that were not represented in the literature, these were reassigned to their closest welding process, base metal, and consumable in the scenarios. Galvanized steel was regrouped with mild steel, MCAW was regrouped with GMAW, E6010 with E6011, E316 with E308, E70CM6 and ER70S2 with ER70S6, and ER4043 with ER5356. Only 7 of the 21 samples (33%) fell between their predicted confidence intervals. All but one of the observed mean particulate concentrations were larger than the upper bounds of their predicted confidence intervals. Following that, a confidence interval around the observed values was computed by assuming a 10% margin of error [16] and examined to see whether these confidence intervals overlapped with their predicted confidence intervals. In 62% of cases (13/21), they did overlap. However, when observing the relative position of each mean concentration within their respective source, a Spearman's rho of 0.64 ($p < 0.005$) was observed, suggesting a high degree of agreement between the values from the experiment and those from the literature. This meant that it would be possible to calibrate the model by combining the literature values with those from the experiment to produce a final model that could be used for the What-me and What-men exposures.

3.4 Calibration

A combined model of both data from the literature and data from the scenario replications can be seen in Table 6. A factor variable indicating the source of the data was included and was indeed significant, confirming that our sample results were higher than those seen in the literature. Along with calibrating the model, the combined model gave estimates for the welding process, base metal, and consumable that were regrouped in the validation stage, which would enable us to not only make estimates for all of the 21 key scenarios in the What-me and What-men cohorts but also for additional scenarios less often seen in the study. In this calibrated model, FCAW remains the highest-producing process,

Figure 1: *Plot of Observed versus Predicted Values – Fully Adjusted Calibrated Model*



followed immediately by MCAW, GMAW, and MMAW, with the reference category also being the lowest-producing process (GTAW). This result was consistent both with the model from the literature and the mean concentrations from the experiment. With aluminum as the reference category, galvanized steel showed the highest concentration of particulate matter, immediately followed by the unknown/multiples category, stainless steel, mild steel, and high alloyed steel. This result was consistent across both the literature and the results from the experiment, with the exception that mild steel was lower than stainless steel in the calibrated model.

The consumables showed a similar pattern to that in the literature model, with the majority of the significance coming from those consumables that were lower than the unknown/multiple category, with the exception of E71T1 and ER100S, which both showed significantly higher concentrations. The performance of the calibrated model was assessed by plotting the predicted values (fitted) with the observed values (Figure 1). Figure 1 shows that there was a high correlation between the predicted values and the observed values (r = 0.827), and that generally the dots fell randomly around the fitted line, showing that the bias was not caused by a small number of observations.

4. Discussion and Conclusion

Most studies that have tried to develop an exposure matrix have not gone beyond the welding process and base metal combination. There are statistical challenges in attempting to do so, but if a calibrated model could be produced, these challenges could be overcome. Some authors [13] suggest that all that is needed is a welding process and a base metal in order to have a functional exposure matrix accompanied by the magnitude of the work to be completed. This current study, however, was aimed at producing the first three-way exposure matrix that included welding process, base metal, and consumable that could be complemented by additional factors. Confined space and ventilation are both very important predictors of welding exposures [12], [20], [21] and although not mentioned here, will be included in the final exposure estimates produced for the What-me and What-men cohorts. Some authors have discussed differences in the fumes when comparing different consumables [7] but few have done so as systematically as this study. The results presented here exemplify the importance of including rod/filler metal in an exposure matrix – when one looks at a comparison of ER70S2 versus ER70S6, for example, ER70S6 shows a coefficient that is twice that of ER70S2. This is also exemplified in the comparison of E308 and E316, where it is evident that E308 has a much larger impact on total particulate concentrations than E316. These relationships are likely to explain different metal concentrations when we examine nickel, chromium, or manganese levels. For example, E308 contains half the amount of manganese as E316 and so is expected to produce a lower manganese particulate concentration within the same welding process and base metal. ER308, a consumable for GMAW or GTAW, has the same amount of manganese as ER316 but half the nickel content and more than twice the chromium content, which supports the contention that these details cannot safely be ignored in developing an exposure model.

The samples collected in this study produced higher concentrations of total particulates than what is seen in the literature. This most likely reflects the concern to avoid undetected metal concentrations in the scenarios that produce the lowest fumes. To minimize this possibility, the ventilation in the welding laboratory was turned off for the duration of the welding. Additionally, the participant welded non-stop for the entire sampling duration of three hours whether or not the room was filled with suspended particles. Again, this was done to maximize the amount of material gathered on the filters. The samples collected may not be as representative of certain occupational settings for these reasons but overall remain in high agreement with the literature.

A complete analysis of metal concentrations still has to be performed and estimates have to be produced for these. Additionally, the estimates obtained from this study will be used to make exposure estimates in the What-me and What-men cohorts, and these estimates will be tested against health outcomes, particularly in pregnancy, together with other conditions, predominantly dermatitis and asthma.

Table 1: *Most Common Scenarios Found in the What-me and What-men Cohorts*

Process	Metal	Consumable	n	n_e	[1]Mean (µg/m^3)
MMAW	ms	E6010	272	4	9777
MMAW	ms	E7018	1081	5	6198
MMAW	gs	E6010	16	2	13275
MMAW	gs	E7018	74	2	12985
MMAW	ss	E308	27	3	1707
MMAW	ss	E316	22	3	4975
GMAW	ms	ER70S6	700	3	21275
GMAW	ms	ER70S2	30	2	13054
GMAW	gs	ER70S6	49	2	17966
GMAW	ss	ER308L	21	4	6889
GMAW	ss	ER316L	7	2	1172
GMAW	al	ER5356	49	3	2214
GMAW	al	ER4043	17	4	3773
FCAW	ms	E71T1	147	4	60838
MCAW	ms	E70MC6	51	4	12961
GTAW	ms	ER70S2	62	2	1275
GTAW	ms	ER70S6	34	2	1248
GTAW	ss	ER316L	48	3	1085
GTAW	ss	ER308L	46	2	387
GTAW	al	ER5356	21	3	1041
GTAW	al	ER4043	21	2	527
Total number of combinations covered by selected scenarios:			2795	61	
Total number of scenarios with matching consumable and base metal:			3086		

*ms = mild steel, gs = galvanized steel, ss = stainless steel, al = aluminum, n_e = number of experiments
[1]mean concentrations from welding scenario replications

Table 2: *Mean Concentrations of Total Particulates from the Welding Experiment (μg/m³)*

Process	Mean(ln)	Mean	SD	n
MMAW	8.924	7508.508	5054.170	19
GMAW	9.121	9143.563	8031.537	20
GTAW	6.853	946.600	389.277	14
FCAW	11.016	60837.632	23597.229	4
MCAW	9.470	12961.005	7041.348	4
Metal				
Mild steel	9.781	17702.789	21571.700	26
Stainless steel	8.063	3174.800	2937.891	17
Aluminum	7.607	2012.851	1454.365	12
Galvanized steel	9.598	14741.806	5108.411	6
Consumable				
E6010	9.300	10943.149	5179.484	6
E7018	9.004	8137.060	4440.644	7
E308L	7.442	1706.504	304.110	3
E316L	8.512	4974.607	2585.475	3
ER70S6	9.589	14607.496	10288.670	7
ER70S2	8.877	7164.502	7102.952	4
E71T1	11.016	60837.632	23597.229	4
E70C6M	9.470	12961.005	7041.348	4
ER308L	8.460	4721.596	3812.645	6
ER5356T	7.395	1627.724	1081.050	6
ER316L	7.021	1119.740	227.060	5
ER4043	7.814	2475.003	1826.922	6

*n = number of replicates

***Table 3:** Mean Concentrations of Total Particulates from the Literature (μg/m³)*

Process	Mean (ln)	Mean	SD	n_p	n_l	n_t
MMAW	7.922	2756.067	2.117	21	50	1178
GMAW	7.771	2370.694	1.907	26	68	1343
GTAW	6.471	645.823	1.993	14	23	835
FCAW	8.813	6722.598	1.515	7	11	280
Metal						
Mild steel	7.826	2504.201	2.374	16	32	384
Stainless steel	7.134	1254.024	2.502	13	32	570
Aluminum	7.746	2312.506	1.992	4	28	209
High alloyed steel	7.545	1892.140	2.104	3	12	34
Unknown or multiple	7.664	2129.444	2.622	16	48	2439
Consumable						
E11018	8.021	3045.383	5.101	1	3	3
E308	8.039	3099.999		1	1	71
E309	7.953	2844.114	1.454	2	5	75
E6011	7.641	2081.633	1.607	1	2	4
E7018	7.040	1141.000		1	1	1
E71T1	8.905	7370.000		1	1	29
ER100S	8.171	3535.747	1.376	3	8	36
ER308	6.881	973.242	1.160	2	2	2
ER309	6.881	973.242	1.320	2	2	42
ER316	7.824	2500.000		1	1	12
ER5356	7.824	2498.693	3.088	2	25	74
ER70S6	7.666	2135.276	1.447	1	2	20
TECH276	6.506	669.013	2.374	1	2	2
FC308	6.305	547.280		1	1	7
Unknown or multiple	7.583	1964.453	2.612	32	97	3329
Sample type						
Respirable fraction	7.266	1431.351	3.124	19	34	1050
Total particulates	7.737	2292.461	2.291	29	118	2586

*n_p = number of papers, n_l = number of lines of data (means), n_t = total number of samples

***Table 4:** Univariate Model of Mean Total Particulates from the Literature (ln μg/m³)*

			95% CI	
Process	**ß coef**	**SE**	**Lower**	**Upper**
MMAW	1.190	0.068	1.056	1.324
GMAW	1.630	0.123	1.389	1.871
FCAW	2.560	0.178	2.211	2.908
GTAW	rc	rc	rc	rc
Metal				
Mild steel	0.521	0.283	-0.035	1.076
Stainless steel	-0.898	0.143	-1.179	-0.617
High alloyed steel	-0.514	0.213	-0.932	-0.097
Unknown or multiple	-0.614	0.581	-1.753	0.525
Aluminum	rc	rc	rc	rc
Consumable				
E11018	0.596	0.433	-0.252	1.444
E308	0.389	0.172	0.052	0.726
E309	-0.799	0.593	-1.961	0.363
E6011	-0.009	0.172	-0.346	0.328
E7018	-0.386	0.433	-1.233	0.462
E71T1	1.807	0.367	1.087	2.526
ER100S	1.033	0.374	0.301	1.766
ER308	-1.410	0.433	-2.258	-0.562
ER309	-0.769	0.172	-1.106	-0.432
ER316	0.174	0.172	-0.163	0.512
ER5356	0.080	0.241	-0.392	0.553
ER70S6	0.017	0.172	-0.320	0.354
TECH276	-0.919	0.433	-1.767	-0.072
FC308	-1.345	0.172	-1.682	-1.008
Unknown or multiple	rc	rc	rc	rc
Sample type				
Respirable fraction	-0.075	0.222	-0.509	0.360
Total particulates	rc	rc	rc	rc

Frequency weighted linear mixed model with journal article as random effect and number of samples as weight.
*rc = reference category

Table 5: *Multivariate Model of Mean Total Particulates from the Literature (ln µg/m³)*

			95% CI	
Process	**ß coef**	**SE**	**Lower**	**Upper**
MMAW	1.224	0.079	1.070	1.378
GMAW	1.683	0.111	1.465	1.900
FCAW	2.649	0.195	2.267	3.031
GTAW	rc	rc	rc	rc
Metal				
Mild steel	0.541	0.159	0.229	0.853
Stainless steel	0.687	0.106	0.480	0.894
High alloyed steel	0.488	0.115	0.262	0.713
Unknown or multiple	0.718	0.284	0.161	1.275
Aluminum	rc	rc	rc	rc
Consumable				
E11018	0.027	0.291	-0.544	0.597
E308	0.495	0.285	-0.063	1.054
E309	-1.776	0.286	-2.337	-1.215
E6011	0.077	0.285	-0.482	0.637
E7018	-0.955	0.291	-1.525	-0.384
E71T1	0.136	0.306	-0.464	0.736
ER100S	0.316	0.287	-0.247	0.879
ER308	-0.960	0.264	-1.477	-0.443
ER309	-1.287	0.211	-1.699	-0.874
ER316	-0.178	0.226	-0.621	0.265
ER5356	0.391	0.444	-0.479	1.260
ER70S6	-0.521	0.266	-1.042	0.000
TECH276	-1.947	0.282	-2.499	-1.395
FC308	-2.664	0.234	-3.122	-2.205
Unknown or multiple	rc	rc	rc	rc
Sample type				
Respirable fraction	-0.330	0.131	-0.587	-0.072
Total particulates	rc	rc	rc	rc
Constant	5.963	0.236	5.500	6.425

Frequency weighted linear mixed model with journal article as random effect and number of samples as weight.
*rc = reference category

***Table 6:** Calibrated Multivariate Model of Mean Total Particulates from the Literature (ln μg/m³)*

			95% CI	
Process	**ß coef**	**SE**	**Lower**	**Upper**
MMAW	1.225	0.079	1.071	1.378
GMAW	1.683	0.108	1.472	1.895
FCAW	2.649	0.193	2.271	3.026
MCAW	2.239	0.448	1.361	3.118
GTAW	rc	rc	rc	rc
Metal				
Mild steel	0.552	0.163	0.233	0.871
Stainless steel	0.691	0.103	0.489	0.893
High alloyed steel	0.450	0.108	0.238	0.663
Galvanized steel	1.039	0.159	0.726	1.351
Unknown or multiple	0.723	0.282	0.170	1.275
Aluminum	rc	rc	rc	rc
Consumable				
E11018	0.807	0.427	-0.030	1.643
E308L	-1.104	0.453	-1.991	-0.217
E309L	-1.032	0.420	-1.855	-0.208
E316L	-0.082	0.434	-0.932	0.768
E6010	0.672	0.454	-0.217	1.562
E6011	0.072	0.284	-0.486	0.629
E7018	0.284	0.464	-0.626	1.193
E71T1	1.045	0.466	0.131	1.959
ER100S	1.201	0.444	0.331	2.071
ER308L	-0.515	0.416	-1.330	0.301
ER309L	-0.243	0.418	-1.063	0.576
ER316L	-1.008	0.412	-1.815	-0.201
ER4043	0.025	0.424	-0.807	0.856
ER5356	-0.178	0.424	-1.009	0.653
ER70S2	0.241	0.445	-0.631	1.114
ER70S6	0.521	0.447	-0.354	1.397
TECH276	-1.168	0.426	-2.003	-0.333
FC308L	-2.662	0.234	-3.120	-2.204
Unknown or multiple	rc	rc	rc	rc
Sample type				
Respirable fraction	-0.330	0.131	-0.587	-0.073
Total particulates	rc	rc	rc	rc
Source				
Experiment	0.721	0.359	0.017	1.426
Systematic review	rc	rc	rc	rc
Constant	5.957	0.234	5.498	6.417

Frequency weighted linear mixed model with journal article as random effect and number of samples as weight.
*rc = reference category

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Appendix A

Task questionnaire

Subroutine 1

1 At what time did you start this type of welding? ____________ AM/PM

2 At what time did you stop this type of welding? ____________ AM/PM

3 For how long were you actually doing this type of welding? ____________ DURATION (HRS/MINS)

4 What were you welding? Please describe in your own words the things/pieces you were joining:

____

____

____

____

5 What materials did you handle (i.e., what types of base metal were you welding)?
(tick as many as appropriate)

Materials	Yes	No
5.1 Mild steel/carbon steel/low alloy		
5.2 High chrome/stainless steel		
5.3 Other high alloy steel (please specify ______________________)		
5.4 Cast iron		
5.5 Galvanized steel		
5.6 Other plated steel (please specify ______________________)		
5.7 Aluminium		
5.8 Copper		
5.9 Bronze		
5.10 Lead		
5.11 Other (please specify ______________________)		

6 Which, if any, of the following filler rods or wires did you use?
(tick as many as appropriate)

Materials	Yes	No
6.1 Mild steel/carbon steel/low alloy 6.1.2 If yes, please specify main rods or wires used: ______		
6.2 High chrome/stainless/alloy 6.2.1 If yes, please specify main rods or wires used: ______		
6.3 Other 6.3.1 If yes, please specify main rods or wires used: ______		

7 Did you use fluxes while doing this type of welding on this day? ☐ Yes ☐ No

7.1 If ***yes,*** what type?

☐ 7.1.1 incorporated in to rod/wire

☐ 7.1.2 ***not*** incorporated into rod/wire

8 Did you use a shielding gas while doing this type of welding on this day? ☐ Yes ☐ No

8.1 If ***yes,*** which gas?

☐ 8.1.1 Argon

☐ 8.1.2 Other inert gas

☐ 8.1.3 CO_2

☐ 8.1.2 Other inert gas

☐ 8.1.4 Argon / CO_2 mixture

☐ 8.1.5 Other **(please specify** ______)

9 Were any of the metals you worked on while doing this type of welding coated? ☐ Yes ☐ No

9.1 If ***yes,*** what were they coated with?

9.1.1 Paints or primers

If coated with paints or primers, what kind were they?

☐ 9.1.1.1 Lead oxide (red lead)

☐ 9.1.1.2 Lead chromate

☐ 9.1.1.3 Zinc chromate

☐ 9.1.1.4 Iron oxide

☐ 9.1.1.5 Epoxy

☐ 9.1.1.6 Other **(please specify** ______)

10 What proportion of your time when doing this type of welding on this day did you work indoors or outdoors?

__________ % INDOORS __________ % OUTDOORS

10.1 If you worked indoors, was it in a confined or enclosed space? ☐ Yes ☐ No

10.2 If you worked in a confined or enclosed space, what was the proportion of your time? __________ %

Appendix B

Template used for data extraction

Citation		Usable Data Y or N		Extracted by	JM	Sheet #	1 of 1

Raw data	
Smpl Year	
# welders	
# sites	
Location	
Industry	

Comments

Weeding and Sampling Scenarios

Welding	Process	Rod/ electrode	Shielding gas/ flux	Base metal	Coating	Ventilation	Comments
1							
2							
3							
4							
5							
6							

Sampling	tot/inhal/ resp/nano	or Collection method	Sample time	Personal (P)	Task (T) or shift (S)	Comments	
A							
B							
C							
D							
E							

Air Sample Results-Fumes

Welding Scenario	Sampling Scenario	Analysis	Metal							Total Particulates
			Units							mg/m³
			n							
			Mean							
			SD							
			Median							
			GM							
			GSD							
			Range							
			n							
			Mean							
			SD							
			Median							
			GM							
			GSD							
			Range							
			n							
			Mean							
			SD							
			Median							
			GM							
			GSD							
			Range							

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