Validation of Training Concepts for Effective Ventilation Control for Welding Fumes in Confined Spaces

Lea Duffin

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Committee Members:

Dr. Noah Seixas

Dr. Mike Yost

Gerry Croteau, MS, CIH

Program Authorized to Offer Degree:

Public Health—Department of Environmental and Occupational Health Sciences

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Introduction

Welding is an important occupation in the United States (U.S.) with over 300,000 workers in the welding, soldering, and brazing operations and with over 13,000 shipyard welders in the U.S. (1). Welding occupations have unique and significant risks associated with occupational safety and exposure to metal fume. Health risks for shipyard welders include exposures from coated surfaces (e.g., lead paint) and hazards associated with confined spaces including asphyxiation, higher risk of fire or explosion, entrapment, and other hazards (2). Working in confined spaces can lead to contaminant concentrations two-fold higher than in non-confined spaces (3). Furthermore, the hulls of the ships are complex and may only have one entrance, making adequate ventilation setup difficult.

Depending on the type of welding, the base metal alloy composition, and the coating on the metal, welders can be exposed to zinc, cadmium, iron oxide, mercury, lead, antimony, arsenic, beryllium, manganese, nickel, molybdenum, chromium, cobalt, copper, fluorides, chlorinated hydrocarbon solvents, phosgene, carbon monoxide, ozone, nitrogen oxides, ultraviolet light, and infrared light (4) (5). A study conducted in 2005 found that 90% of particles in welding fume are ultrafine with an aerodynamic mass median diameter less than 1µm (6). Ultrafine particles can reach the alveolar region of the lung and there is increasing evidence that these particles can exacerbate existing respiratory symptoms (7). A study by Oberdörster and colleagues found evidence that ultrafine particles can translocate across the blood brain barrier using animal models, which is a significant concern for central nervous system damage (8).

Occupational illnesses associated with welding fume include “welding fume fever,” pneumoconiosis, abnormalities in sperm, and possible infertility in welding workers (9). The

International Agency for Research on Cancer reported welding fume as a probable carcinogen, classification group 2B, as it may cause an increased risk of lung cancer (10). A meta-analysis of welding fume and cancer research conducted by Amriose et al., found a 26% excess of lung cancer incidences in welding populations. Smoking was not found to be a confounding factor and the effect of asbestos could not be measured (11). Excess lung cancer deaths were also found in U.S. Coast-Guard shipyard welding populations with a standardized mortality ratio (SMR) of 1.34, while the entire shipyard worker population had a SMR of 1.08 including lung cancer and mesothelioma fatalities (12). After adjusting for smoking, a population-based case control study in Italy found that welders had an odds ratio for lung cancer of 5.6 (95% confidence interval of 2.1-15) (13).

Over the past few years several research projects have addressed the potential link between Parkinsonism and manganese exposure in welding fume. Manganese, a neurotoxin, is found in the base metal and filler wire used in welding processes and can comprise 4% of total particulate mass (14) (15). Studies have shown that welders had a higher rate of Parkinsonism (16) and that welding fume exposure could be a risk factor for the idiopathic Parkinson's disease (17). Parkinsonism symptoms reported in welders include tremors, rigidity, and postural instability (15). Additionally, studies have shown that welders' exposures can commonly exceed exposures limits set by research organizations increasing the risk of neurological diseases and symptoms (14).

Since there are many different components in welding fumes, there are no specific federal standards for welding fume concentration levels at shipyards. Therefore, welding fume standards typically fall under the federal Occupational Safety and Health Administration (OSHA) standard for particulates not otherwise regulated, which 15 mg/m^3 for an 8-hour time weighted average

TWA (18). The Washington Administrative Code Permissible Exposure Limit (WAC PEL) and the American Conference of Governmental Industrial Hygienists Threshold Limit Value (TLV) for welding fume is 5 mg/m^3 for an 8-hour TWA (19) (20).

Ventilation Control

There are no federal standards specifying an adequate ventilation flow rate for control of welding fumes in shipyards as seen in general industry and construction standards. The federal shipyard standards state that ventilation shall be provided when there is an accumulation of contaminants in confined spaces (21). The standards state acceptable ventilation can include local exhaust ventilation (LEV) placed as close as practical to the welding fume so that the smoke can be removed to keep concentrations within safe limits as well as general mechanical or dilution ventilation (DV) that provides appropriate air changes to keep fume and smoke concentrations within safe limits. Additionally, LEV shall be used when welding on surfaces that contain lead, cadmium, mercury, and beryllium in confined spaces (21).

In a study by Wurzelbacher and colleagues, LEV was found to be more effective than DV in decreasing welding fume concentration in shipyard confined spaces (22). LEV is typically only effective when positioned properly and the LEV opening is less than 12 inches from the welding source (23). However, the welder's body position can affect the efficiency of the LEV ventilation in reducing personal breathing zone (PBZ) contaminant levels especially if the worker is blocking the LEV opening. The effect of body position on the efficiency of the LEV has been reported by other studies as well. One study reported one in four welders effectively used LEV during their investigations (3). A review by Flynn and Susi noted the welder position affected the efficiency of LEV and that the welder's head was near the plume. Additionally, in-field assessments of LEV showed lower efficiency in welding fume removal than in controlled settings due to additional work activities that can create dust typically seen in real-world environments (14).

Assessments of shipyard welders conducted by the University of Washington found that only a small percentage of welders use LEV and do not use it effectively (24). Welders at two shipyards, one in Washington State and the other in Alaska, were observed and monitored for total particulate concentrations. Of the 125 samples collected, only 3% used LEV, 29% used DV, and 68% did not use LEV or DV. Additionally, 82% of workers were exposed to atmospheres that exceeded the 5 mg/m^3 8-hour WAC PEL TWA. In confined spaces and enclosed spaces, 94% and 70% of the samples exceeded the WAC PEL, respectively. DV and LEV were reported in 31% and 100% of the samples that exceeded the WAC PEL, respectively. Furthermore, respirator use was reported in 41% of the samples that exceeded the WAC PEL, and 14% that did not exceed the WAC PEL.

Determinants of exposure level include arc time, work area configuration, the welder/welding positions, degree of enclosure, ventilation effectiveness, and work speed (25) (22) (15). Flux core arc welding (FCAW), a common welding method in shipyards, produces the most fume per unit time compared to other types of welding (25). However, variations in welding fume concentrations in the breathing zone remain a major concern in quantifying such measures. Additionally, in-field studies have noted that there may be multiple sources of exposure to welders as other activities typically are occurring in the same area (14).

Project Overview

Training on proper ventilation setup is vital to control hazardous fume sources in confined space welding. However, previous research has shown that effective ventilation is lacking and workers are still being exposed to hazardous fume above the regulatory and scientific thresholds (24). It was hypothesized that manipulating key aspects of the ventilation system would decrease the concentration of welding fume exposures. The purpose of this study was to determine if the key ventilation training parameters were effective in reducing the welding fume concentration under real-world shipyard confined spaces. Based on these findings, the training program can be validated as providing effective recommendations.

Description of Training Parameters

The training was developed to consider the dynamic welding environment. The welders frequently move throughout and between the work spaces without reconfiguring the ventilation setup. Since LEV is highly dependent on the hood opening to be within approximately 12 inches of the weld source (one duct diameter), it becomes ineffective as the worker moves out of this range during welding tasks. Since DV mixes the space, it can be placed centrally and does not need to be adjusted as the welder moves. The training incorporated these concepts and discussed how to determine what ventilation type to use and additional setup factors to consider. The main concepts covered were the ventilation box model (number of blowers), exhausting versus blowing air, real-world fume production characteristics (e.g., highest near the source and at the ceiling), crossdrafts, mixing, and eliminating short-circuiting. See Table 1 for training parameter descriptions and images.

The adjustments for this study were selected to reduce welding fume concentration in the confined spaces even during dynamic work environments seen in shipyards. The adjustments were as follows:

1. The ventilation rate: The box model is useful in determining the number of blowers a space may need to provide adequate air flow and air changes per minute (ACM). The larger the space, the more blowers are required. The box model is dependent upon the number of welders in the space and the space size. The more welders in a space, there is a higher emission rate of fume production. Additionally, the smaller the space size, the faster the space fills up with the fume.
2. Exhausting versus blowing air: Air velocity decreases with distance more rapidly when exhausting air than blowing air. Exhausting air, therefore, does not have as far of a reach as blowing air (or diluting the air) and has to be located close or centrally in the space whereas the dilution blowers can be placed further away from the welding source to blow air into the space and provide mixing.
3. Exhausting placement: Due to the dynamic work environment, welding can require movement throughout the space necessitating constant movement of the LEV to be effective. Additionally, general exhaust ventilation (GEV) may not provide effective fume removal because of its remoteness. In these situations, it was hypothesized that creating a regional exhaust ventilation (REV) system can provide ventilation control of the hazardous fume, does not have to be moved constantly and is not as affected by welder position. Location of regional exhaust included:

a. High vs. low: Locating the ventilation near the ceiling (where the welding fume rises) captures the most welding fume. Low exhaust placement may reduce the concentration, but is not as effective.

b. Near vs. far: Locating the ventilation near the welding source is the most effective in capturing the fume. The further away the ventilation is located, the less effective the system becomes at capturing the hazardous fume. Regional ventilation allows for the welder to move throughout the space without constantly moving the ventilation.

4. Crossdrafts: Creating a crossdraft by adding a blower or mini-fan to provide fresh air across the worker's PBZ is effective in reducing fume exposure. However, it requires a close proximity of the blower to the welder to provide an appropriate air flow rate. A mini-fan was modified to be used in the shipyard (see Figure 1). The mini-fan can be placed on any metal surface and pointed at the welder's breathing zone. The air flow rate is adjustable. The mini-fan was designed to be easy to carry into confined spaces and place on any metal surface for support.

Figure 1. Mini-fan

5. Mixing: Increasing the mixing of the air in the space by providing more supply blowers or changing the blower configuration can reduce fume concentration in the space by

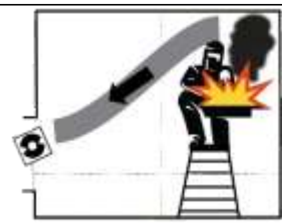
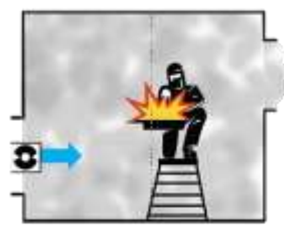
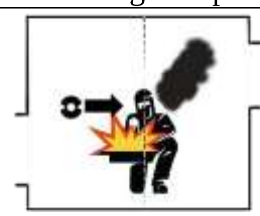
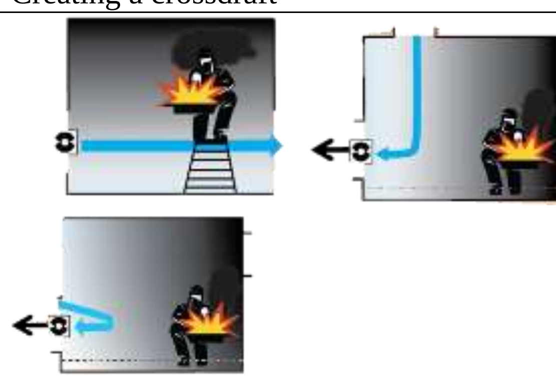
introducing a mixing factor. Mixing also allows for the depletion of dead spaces, especially in large rooms where exhaust ventilation may not have a far reach unlike DV.

6. Elimination of short-circuiting situations: When short-circuiting situations are present, the efficiency of the ventilation system can drop dramatically to the point that it is not reducing the fume concentration in the space or at the welder. Eliminating these situations will improve the ventilation's efficiency.

The adjustments selected for this study were REV (high, low, near, and far), mixing created by dilution ventilation, and creating a crossdraft with a mini-fan. Short-circuiting situations were not found in the shipyard since existing ventilation was not usually set up in the confined space and was, therefore, excluded from the parameters tested in the field.

Table 1. Training Parameter Descriptions

Training Parameters	**Description**	**Image**
The Ventilation Rate (The Box Model)	Useful in determining the number of blowers a space may need to provide adequate air flow and ACM considering number of welders, emission rates, and space size.	 Increasing the number of blowers, decreases concentration  More welders, higher emission rates  Smaller space sizes, faster fume builds up

Blowing vs. Exhausting Air	Blowing air (DV) has a further reach than exhausting air (LEV/REV/GEV).	 Blowing air has a further reach than exhausting air
Regional Exhaust Ventilation vs. General exhaust	REV is located centrally in the space; near the ceiling to collect more welding fume as compared to GEV.	  GEV—Less reach REV—Further reach
Regional Exhaust Ventilation Near vs. Far	Locating the ventilation near the welding source is the most effective in capturing the fume.	  Near—Shorter reach Far—Less reach
Dilution Ventilation-Mixing	Increasing the mixing of the air can reduce fume concentration in the space. Mixing also allows for the depletion of dead spaces.	  Exhausting the space Dilution-Mixing
Creating Crossdrafts	Creating a crossdraft can provide fresh air across the worker's PBZ and blows the smoke away from the welder	 Creating a crossdraft
Eliminating Short-Circuiting	Eliminating short-circuiting situations when they are present can increase the effectiveness of the present ventilation system.	 Eliminate Short-Circuiting Situations

Methods

The study was conducted at a shipyard in Seattle, Washington and focused on the construction of two new ferries. An observational tool (see Appendix 1) was created to provide general characterization of the space, type of welding, ventilation setup, and ventilation effectiveness. A TSI Velocicalc 9565 was used to measure the air velocity of the ventilation equipment. To monitor welding fume concentration, a MIE Personal DataRam™ (pDR) was used along with a SKC Aircheck XR5000 pump to collect aerosol concentrations. These were set in series and were calibrated before each use with a DryCal calibrator at 2 L/min. See Figure 2 for sampling train setup.

Figure 2. Sampling set up with pDR and SKC Aircheck Pump

At the start of each working shift, the worker was fitted with the sampling device in order to collect measurements at the worker's breathing zone. The opening was positioned outside of the welding hood on the collar or shirt of the welder to better reflect room conditions and because it was hypothesized that the welding fume could concentrate inside of the helmet.

In order to determine how the ventilation would affect the concentration in the confined space and, hypothetically, other workers in the space, an additional area sample was collected. An area pDR was placed centrally in the room, hanging from the ceiling or above the worker on a wall. The area pDR was typically placed within a 5-foot radius of the welder.

Study Design

A number of criteria had to be met in order to collect samples in the confined space. This included predicting the welding duration, the capability to provide adjustments in the confined space, and obtaining consent from the worker. After in-field zeroing of the equipment, the pDR was placed on the worker and in the space.

During the pre-adjustment period (the control), the worker welded in the confined space. The observation form was completed and the time spent welding was simultaneously recorded. Typically, there was no ventilation already set up in the space during the pre-adjustment period.

The adjustments of the ventilation were set up between the pre- and post-adjustment periods. The adjustments included: adding an exhaust blower and positioning it high or low, or near or far from the worker; adding a supply blower to mix the air in the space; and creating a crossdraft with a mini-fan. Adjustments were selected by the feasibility of setting up the ventilation in the space, number of workers, as well as the space size and degree of enclosure. During the post-adjustment period (the treatment), the worker was observed welding again and time spent welding was recorded. Ventilation airflow and effectiveness was noted on a new observation form.

If there was enough welding time, additional adjustments or repeat adjustments were made in the space. Typically if multiple adjustments occurred, they switched between high and low or near and far proximities to the welding source, as well as switching between pre-adjustments and post-adjustments (such as turning the fan on and off).

Data Analysis

The concentration measurements were 10-second averages of total particulate concentrations in milligrams per meter cubed (mg/m^3) as illustrated by Figure 3. Measurements for each day were then separated into “runs.” Each pre- and post-adjustment was defined by its own run. Multiple runs in the same space were grouped into “sets.” Sets included both pre- and post-adjustments that were matched by the time and by the space since the workers moved spaces frequently. If the welder moved to a new room, a new set of runs were defined. In some sets, there were multiple post-adjustments to a single pre-adjustment reference condition. Breaks were excluded from analysis as the welder was neither welding nor located in the space.

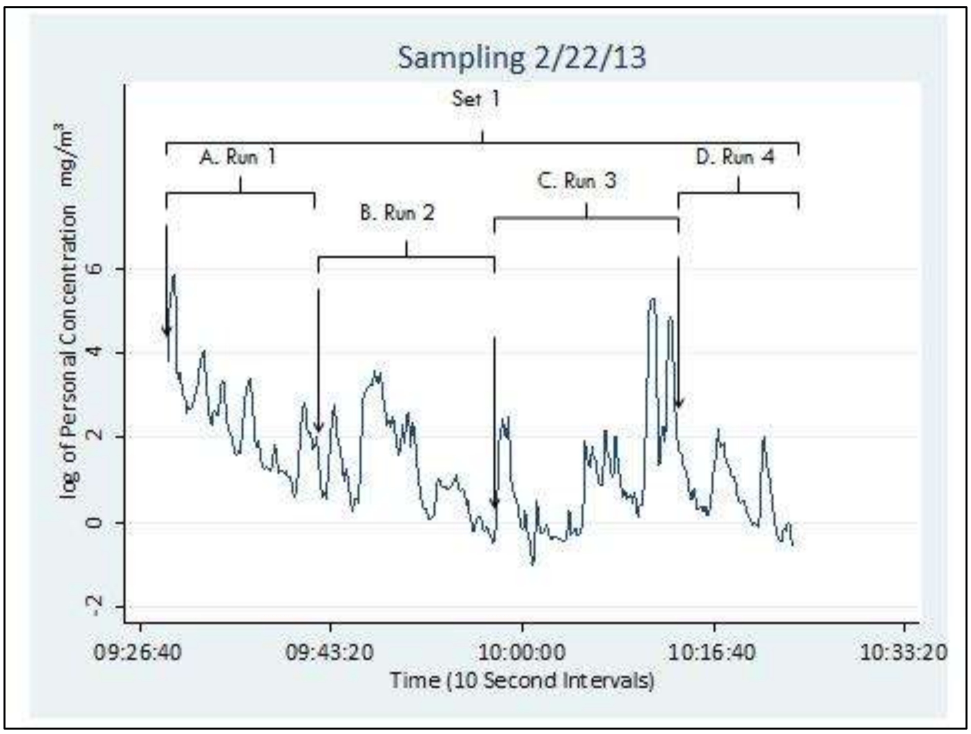


Figure 3. Sampling Set 1 from 2/22/2013 (in mg/m^3)

A. Pre-adjustment 1, Run 1: No Ventilation (GM: 11.65, GSD: 3.10, 90^{th}: 44.0)
B. Post-adjustment 1, Run 2: Exhaust Blower, Far (GM: 4.49, GSD: 2.80, 90^{th}: 21.85)
C. Pre-adjustment 2, Run 3: No Ventilation (GM: 2.50, GSD: 4.20, 90^{th}: 11.72)
D. Post-adjustment 2, Run 4: Exhaust Blower, Near (GM: 2.22, GSD: 2.60, 90^{th}: 6.45)

Figure 3 demonstrates a typical sampling day or set. The day was separated into runs by the action that occurred, which was two pre-adjustments with no ventilation and two post-adjustments where exhaust ventilation was added either far or near to the welding source.

Descriptive statistics between pre- and post-adjustments and between different adjustment treatments were calculated. Using the 10-second intervals, the geometric means (GM), geometric standard deviations (GSD), and the 90^{th} percentiles (90^{th}) were calculated for each run. The arithmetic mean (AM) and arithmetic standard deviation (ASD) of the GM, GSD, and 90^{th} for all runs were calculated. The 90^{th} percentile was calculated to represent the upper limits of the exposure concentrations that occur during monitoring of welders in confined spaces. Additionally, the AM and the ASD were calculated for overall space and ventilation characteristics including space size, proportion of time spent welding, ACM, and total cubic feet per minute (CFM) for both the control and the treatment.

Box plots for each training parameter were produced to describe the distribution of the concentration and to identify any outliers. Pre- and post- adjustments were matched (from the sets) and the pre-adjustment, or the control, was set to 100% as a reference. The percent change from control was calculated for the post-adjustments. The pre- and post-adjustments are matched in order to make inferences of change in concentration between the two periods abut to also control for determinates of exposures such as type of welding, degree of enclosure of the space, position of the weld, and intra-personal welding habits.

A Student’s t-test was also completed to determine the statistical significance of the difference in the means between the pre- and post-adjustments. An alpha of 0.05 was determined as significant in the comparisons for the p-values. To graphically represent each sampling period, or day, the data was logged to control for the skewed behavior of exposure models.

One run outlier was identified by graphically representing the sampling period and was eliminated based on comparison to all other runs. The control run (pre-adjustment) was 22 times lower than other the other control runs. Since that run was matched to a post-adjustment, the set including both runs were excluded from. Some runs were not used due inadequate data or because they could not be matched between pre- and post-adjustment and developed into a set. For example, there may have only been one pre-adjustment before the welder switched into a new space and therefore no matched post-adjustment occurred. This type of run was excluded from analysis.

Results

Over 16 days of sampling, 34 sets of data comprising 87 runs were collected. There were 36 runs with no ventilation (pre-adjustment or control) and 51 runs with ventilation (post-adjustment or treatment). The post-adjustments consisted of high (n=11), low (n=9), near (n=5), far (n=6), crossdraft (n=4), and mixing (n=5). All but one day of sampling was performed using flux core duel shield welding methods.

These samples were not collected for a typical 8-hour WAC PEL TWA; however, this limit does provide a threshold for comparison of means. Proving that adjustments would fall below the limit would provide additional support for regulatory compliance. For pre-adjustments the percentage of samples that were under the WAC PEL of 5 mg/m^3 was 53% (n=19). For post-adjustments, 80% (n=41) were under the WAC PEL.

Summary statistics are provided in Table 2 for space size and proportion of time spent welding. The space size for the control group was smaller and the proportion spent welding was longer than for the treatment group. The space type, or the degree of enclosure, was similar in proportion between the control and treatment groups.

Table 2. Summary of Space Characteristics and Ventilation Characteristics

Variable	**Control**				**Treatment**			
	n	(%)	AM	(ASD)	n	(%)	AM	(ASD)
Proportion of time spent welding	36	(41)	0.49	(0.43)	51	(59)	0.35	(0.19)
Space Size (ft^3)	36	(41)	718.53	(955.43)	51	(59)	1027.82	(1171.5)
Space Type—Partially Enclosed	10	(28)			17	(33)		
Space Type—Enclosed	17	(47)			25	(49)		
Space Type—Confined	9	(25)			9	(18)		

Table 3 characterizes similar information, the ACM, total CFM, proportion of time spent welding, and space size by each of the six adjustments (high, low, near, far, mixing, and crossdraft). The count, percentage, AM, and ASD are shown. The flow rate of the ventilation was the highest for the regional exhaust ventilation high, low, near or far. The highest ACM was with the low adjustment with 18 ACM. The high and mixing adjustments were above 10 ACM. The proportion of time spent welding ranged between 0.26 and .41 between all adjustments.

Table 4 represents the matched personal and area concentrations provided by the AM and ASD for GM, GSD, and the 90th percentile for the control (pre-adjustment, no ventilation) and the treatment (post-adjustment, ventilation added or positioned differently) for the training variables of interest: high, low, near, far, crossdraft, and mixing. Treatments and controls were matched by the date, room, and the time each occurred. Percent reductions, or the percent change, between pre- and post-adjustments were calculated between control and treatment.

Table 3. Space and Ventilation Characteristics for Each Adjustment

Adjustment Type	n	(%)	Treatment AM	(ASD)
High				
n	23	(42)		
Proportion of time spent welding			0.40	(0.22)
Space Size (ft^3)			989.35	(1000.21)
Total CFM*			2913.62	(587.88)
ACM			12.14	(15.14)
Low				
n	9	(16)		
Proportion of time spent welding			0.41	(0.34)
Space Size (ft^3)			506.00	(671.39)
Total CFM			3415.44	(607.12)
ACM			18.66	(12.05)
Near				
n	7	(13)		
Proportion of time spent welding			0.28	(0.19)
Space Size (ft^3)			1409.86	(1454.54)
Total CFM			2497.34	(1281.13)
ACM			9.97	(13.88)
Far				
n	7	(13)		
Proportion of time spent welding			0.26	(0.15)
Space Size (ft3)			1409.86	(1454.54)
Total CFM			2934.57	(1484.57)
ACM			2.79	(11.44)
Crossdraft				
n	4	(7)		
Proportion of time spent welding			0.39	(0.18)
Space Size (ft^3)			2010.75	(1649.22)
Total CFM			1594.5	(1363.12)
ACM			2.79	(4.28)
Mixing				
n	5	(9)		
Proportion of time spent welding			0.37	(0.08)
Space Size (ft^3)			174.60	(136.38)
Total CFM			1250.60	(552.16)
ACM			11.75	(10.38)

*n=21

Table 4. Personal and Area Concentrations (in mg/m^3)

Variable		Personal							Area						
		Control			Treatment			Change	Control			Treatment			Change
		n	AM	ASD	n	AM	ASD	%	n	AM	ASD	n	AM	ASD	%
High	n	7			11				6			10			
	GM		8.24	10.26		1.95	1.47	-77		17.58	25.24		2.51	2.55	-86
	GSD		2.97	1.13		2.85	1.03	-5		3.70	1.80		2.81	1.10	-24
	90th		19.05	14.71		6.56	6.60	-66		56.62	40.24		8.99*	7.84	-84
Low	n	7			9				6			8			
	GM		7.01	3.06		2.59*	1.80	-66		15.17	21.11		4.46	3.26	-71
	GSD		3.10	1.14		4.03	2.18	23		4.42	2.75		4.76	3.31	7
	90th		17.18	14.32		14.66	7.70	-15		68.23	56.92		45.52	62.52	-33
Near	n	4			5				4			5			
	GM		3.65	3.26		1.83	1.24	-50		4.21	4.61		1.30	1.51	-69
	GSD		4.20	2.04		2.52	1.24	-40		3.28	1.07		3.20	1.83	-2
	90th		15.72	3.75		4.85*	2.40	-69		14.88	11.04		3.65	2.73	-75
Far	n	5			6				4			5			
	GM		5.16	4.62		4.08	2.56	-21		5.07	4.22		3.11	3.15	-39
	GSD		3.90	1.83		2.53	0.80	-38		3.10	1.16		1.89	0.70	-39
	90th		21.20	13.19		15.49	10.50	-37		15.34	10.71		7.89	8.85	-49
Crossdraft	n	3			4				2			3			
	GM		1.42	0.81		3.30	1.26	57		1.44	0.22		1.54	1.26	5
	GSD		4.80	2.13		3.45	3.58	-28		2.85	0.78		1.70	0.40	-40
	90th		9.64	9.19		5.27	2.48	-45		3.29	0.72		6.62*	1.23	50
Mixing	n	5			5				2			2			
	GM		6.37	7.18		1.51	0.54	-76		5.67	6.94		1.50	0.77	-74
	GSD		5.38	3.52		3.68	2.04	-32		3.45	2.05		4.25	2.05	19
	90th		39.50	38.04		5.08	0.59	-87		16.23	10.69		3.87	4.51	-76

* Indicates significant results ($p<0.05$)

Reductions in concentrations were seen for the GM, GSD, and 90th percentiles for the runs positioning the ventilation high, at the ceiling. There was a respective 77% and 86% reduction in the personal and area sample geometric means between the pre- and post-adjustments. This trend was also demonstrated with the 90th percentile area sample with a reduction of 84% between pre- and post-adjustment. Positioning the ventilation low at the floor of the space produced reductions in the GMs and the 90th percentiles for both the personal and area samples. There was a 66% reduction in the personal exposures and a 71% reduction in the area exposures in the GM of the total particulate concentrations. 90th percentile concentration reductions were also observed; however, these were not as profound with 15% and 33% for the personal and area samples. The GSDs between pre- and post-adjustments did not decrease and actually increased slightly.

Locating the ventilation near the welding source produced reductions in total particulate concentrations in all categories, GM, GSD, and 90th percentiles, with both personal and area samples. The most profound of these reductions were in the 90th percentiles of the personal and area samples with a 69% and 75% decrease in concentrations. Similarly, locating the ventilation further from the welding source also produced reductions in total particulate concentrations in the personal and area GM, GSD, and 90th percentiles. The most profound reductions were seen in the 90th percentiles with 37% and 49% in the concentrations between the pre- and post-adjustments. Similar reductions were seen in the GMs for both personal and area samples.

Creating a crossdraft with a mini-fan did not result in a decrease in concentrations between pre- and post-adjustments for the GM. There was a 57% increase in the personal samples and a 5% increase in the area samples when the mini-fan was added. A reduction in the GSDs of the particulate concentration was found in both personal and area adjustments. For the 90th percentiles, a reduction was observed for the personal particulate concentration and a rise in concentrations was observed for the area samples.

Mixing with a supply blower produced reductions in all concentrations for the GM, GSD, and 90^{th} percentile except for the GSD in the area sample, which increased 20%. An 87% and 76% reduction in concentrations for the 90^{th} percentiles were seen in personal and area concentrations, respectively. Additionally, for the GM concentrations, a 76% reduction for the personal samples and a 74% reduction for the area samples were observed.

Several training parameters were considered statistically significant with 95% confidence. These treatments included PBZ low (GM), PBZ near (90^{th}), area high (90^{th}), and area crossdraft (90^{th}). The greatest reductions in changes in concentrations were typically seen in the 90^{th} percentiles. The percent change of the GM, GSD, and 90^{th} percentiles of the pre- and post-matched adjustments for each treatment type were demonstrated in boxplots that were produced (Figures 4, 5, and 6). These boxplots represent personal, breathing zone concentrations.

Figure 4 represents the boxplots for the GM concentration for the different adjustments as a percent of the control. The median change between high, low, near, far, and mixing adjustments were all below the reference line (or the control). The crossdraft median chance was over 100% higher than the control. The interquartile range was larger for the far and crossdraft adjustments. The near and mixing adjustments provided the interquartile range to be completely below the control with a smaller range.

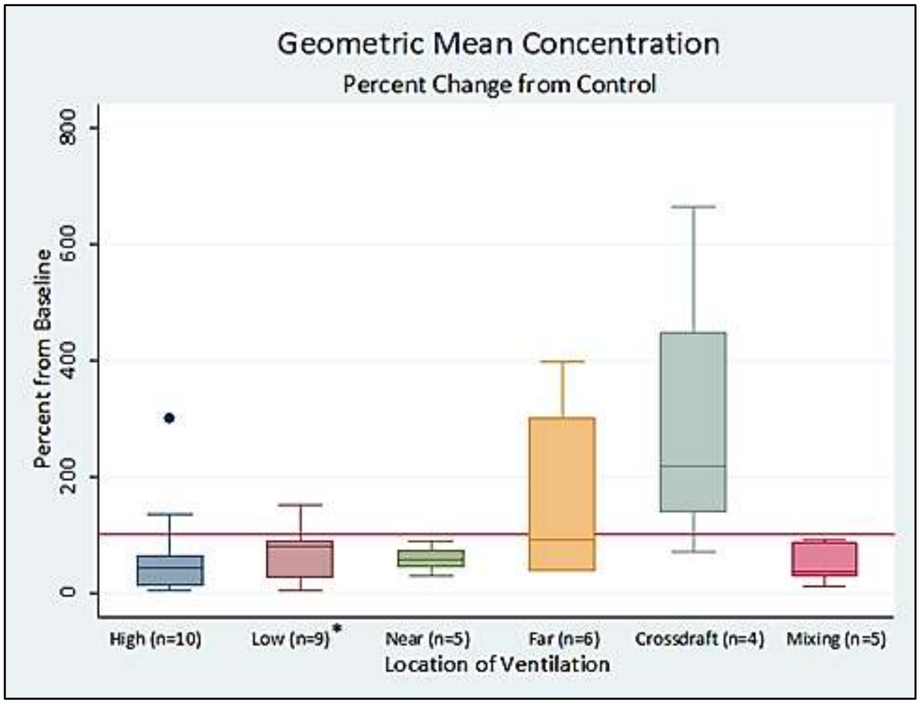


Figure 4. GM Boxplot for Personal Concentration
* Indicates statistically significant results

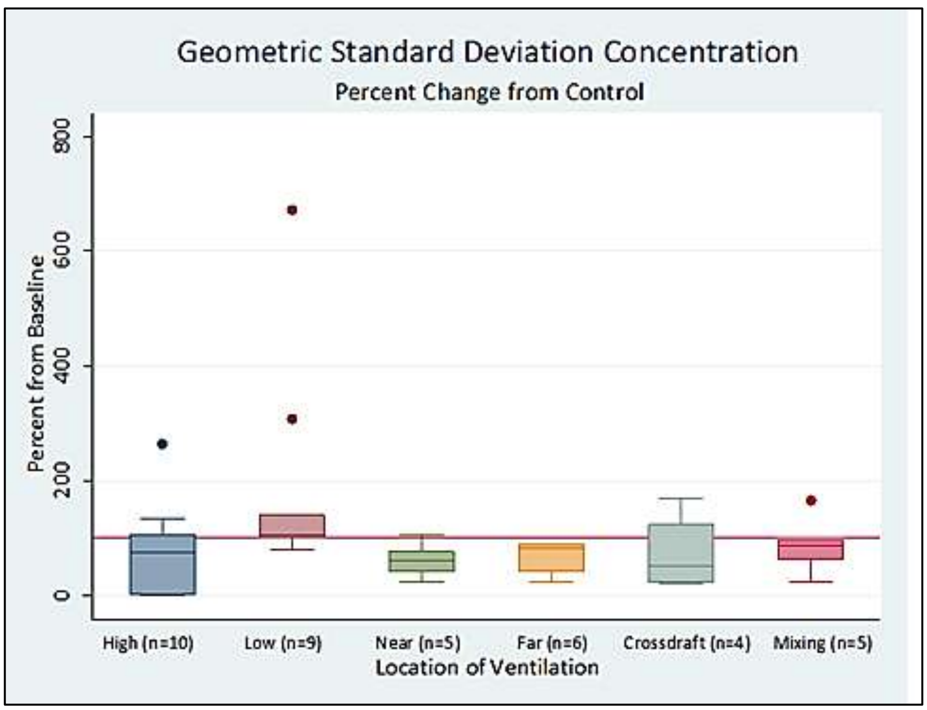


Figure 5. GSD Boxplot for Personal Concentrations

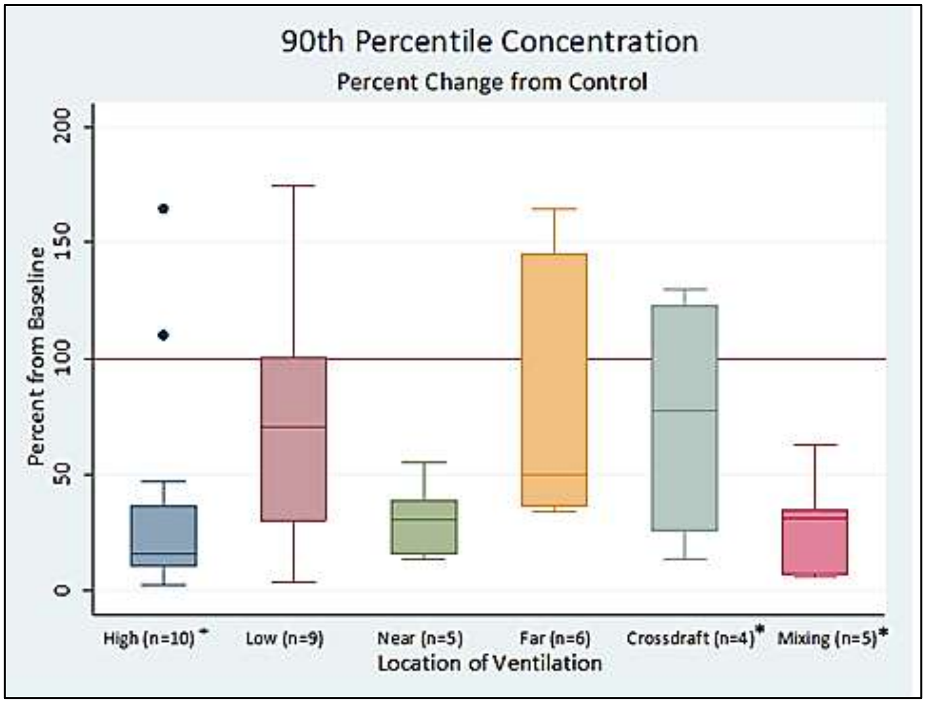


Figure 6. 90th Percentile for Personal Concentration
* Indicates statistically significant results

Figure 5 represents the GSD concentration as a percent change from the control. The interquartile ranges for all of the adjustments were relatively small with a few potential outliers. The medians for high, near, far, crossdraft and mixing were below the control with the low adjustment slightly above 100%. A few potential outliers were present and considered for elimination; however, they were considered valid and kept for analysis.

Figure 6 represents the 90th percentile concentration change from the control. Overall, the interquartile range was very tight for all adjustments ranging from 100% better than the control to under a 100% worse than control. All of the adjustment medians were under the control baseline showing a dramatic decrease in the upper concentration levels for all adjustments.

Discussion

The results of the study found that adding an exhaust blower either high, low, near, or far and mixing the space by adding a supply blower reduces breathing zone concentrations as well as area concentrations of welding fume particulates. The other ventilation concept presented in the training, creating a crossdraft, was less effective and did not result in a consistent reduction in breathing zone or area concentration of welding fume.

Reductions in the GM were observed in most of the adjustment categories (high, low, near, far, and mixing) for both area and personal samples. High reductions in the GM were observed up to almost a 90% change between the pre- and post- adjustment. The interquartile ranges for the adjustments were relatively small, providing consistency in adjustment outcomes. Additionally, for the near and mixing adjustments, the entire range was below the control, showing a certainty in reducing the GM concentrations at the welder's breathing zone.

Observing a decrease in the GSDs demonstrates the adjustments are allowing the welding fume concentration to be less variable and more stable. The boxplots demonstrated that the GSD interquartile ranges for all the adjustments were small and typically (except for the case of low) below the control. The small range demonstrates that the adjustments can provide a sustainable solution for reducing concentration variability. Two adjustments saw an increase in the GSD including the low adjustment (personal and area) and the mixing (area). This is to be expected as the low was predicted to be less effective than the high and compared to no ventilation; the low ventilation adjustment could be creating air currents to pull the welding fume downwards towards the ventilation opening, thus creating more variability in the welding fume concentration.

Reductions were even more pronounced on the 90th percentiles of total particulate concentrations. Reductions were observed in all adjustment categories for both personal and area concentrations except for crossdraft area sample. The increase in 90th percentile concentrations could be attributed to blowing the welding fume towards the area sample. Placing the area sampler away from the mini-fan could have prevented the increase in high exposures. However, the training parameters were very effective in reducing the high concentrations that workers are exposed to in the confined spaces. The highest reduction was observed with mixing, with almost a 90% decrease in concentrations for the personal samples for the 90th percentile concentrations.

Creating a crossdraft did not result in a reduction of welding fume concentration in the breathing zone of the welder or the area sample. There was a relatively small sample size and inferences on the significance of the increase are difficult to ascertain. One reason for the occurrence of the concentration increase could be that the opening for the breathing zone sampler was located on the collar and on the outside of the welding hood (4 to 6 inches from the worker's mouth). A crossdraft was created by placing a magnetic mini-fan on the walls of the space positioned to blow across the breathing zone of the worker (see Figure 7). Therefore, the crossdraft may have only affected the worker's breathing zone whereas the sampler may have been located too far below on the shoulder.

Figure 7. Creating a Crossdraft with a Mini-fan

Other factors that could have affected the particulate concentration at the sampling equipment include the space size and shape as well as which side of the head the sampler was located. If the space was too small, the air moved by the mini-fan could hit the walls of the space and create eddy currents producing incomplete mixing of the space. Additionally, the shoulder in which sampler was located, as well as the direction of the mini-fan air flow was not noted during monitoring. If the sampler was located downwind of the mini-fan and the welder's head, the sampler may have picked up concentration readings higher than what the worker's exposure. Thus, the mini-fan may have, in fact, reduced the particulate concentration in the breathing zone.

Two of three subjects who used the mini-fan asked where they could obtain one for their own personal use. They reacted positively to the mini-fan as they noticed a decrease in welding fume smells, and found it was easier to set up in the confined space. Additionally, the mini-fan could be adjusted to not affect the shielding gas and the weld quality.

Several adjustments were considered significant in either the GM or 90th percentile. Three of the four significant outcomes were at the 90th percentile and this supports the concept that adding the ventilation according to the training parameters (except in the case of creating a crossdraft) resulted in a significant decrease in the most extreme high concentrations. The fact that four conditions were significant could be due to small sample sizes and expected variable atmospheres typically seen with exposure assessments and in-field testing.

There was an increase in the percentage of samples that were under the WAC PEL of 5 mg/m^3 between the pre- and post-adjustments. This demonstrates that the ventilation characteristics not only provide additional control of the welding fume, but also ensure that the concentrations stay below the regulatory limit. While sampling was not conducted for a typical 8-hour work day, it does provide a method for determining that the adjustments can reduce concentrations below a threshold.

There were some differences in general space and ventilation characteristics between adjustments. The regional exhaust ventilation adjustments had a higher overall air flow rate and ACM. However, the proportion of time spent welding, did not vary widely. These differences could potentially have an impact on the concentrations between the different adjustments.

While literature suggests that LEV should be used to control for welding fume in confined spaces (22), the results of this study suggest that REV and DV systems also are effective in reducing welding fume concentrations at the breathing zone and in the confined space area. Reductions in the GM concentration, the GSD, and the 90^{th} percentiles were observed for the high, low, near, far, and mixing adjustments. The welder's position relative to the LEV and the reduced effectiveness of the ventilation system has been observed throughout the literature and persists as a challenge in providing an actual means of welding fume control and education. REV and DV can be easier for the welders to set up and maintain throughout the welding duration, where LEV would require constant movement of the system as well as requiring that the welder pay particular attention to their body position relative to the LEV opening.

Limitations

The sample size of the study was relatively small with 36 pre-adjustments and 51 post-adjustments. Some adjustments had only three or four samples (such as the crossdraft adjustment). Additionally, there was no randomization between pre-adjustment and post-adjustment order. Adding ventilation to the space first and then turning it off to obtain a pre-adjustment could increase the validity of the study. Larger confined spaces were not chosen for the research as many workers were typically in the larger spaces, obtaining IRB consent from all workers was difficult, and there was frequent movement of workers. Larger confined spaces pose additional risks as LEV and REV become more difficult to maintain and using DV (that provides mixing) could have been more effective.

Future Research

Although this research focused on small confined spaces, future research is needed for larger spaces multiple welders, and workers of varying tasks. Testing the welding fume concentration while creating a crossdraft with a mini-fan could be conducted again to further characterize the effects of creating a crossdraft. Eliminating short circuiting was also not addressed and should be addressed in future studies.

Conclusion

Characterization of welding fume and the effectiveness of ventilation have rarely been conducted in the field. Special attention is required in selecting and setting up ventilation due to the unique characteristics of shipyard confined spaces such as constant movement of the welders and limited accessibility to the confined spaces. The training provided in this study considered shipyard confined space welding situations and promoted regional exhaust ventilation, dilution ventilation mixing, as well as creating a crossdraft as possible effective ventilation measures.

Tested in the field, regional exhaust ventilation (whether positioned high, low, near or far) and mixing provided a decrease in welding fume personal breathing zone and area concentrations. Regional exhaust ventilation and dilution ventilation mixing are easier to set up and use and they effectively reduce welding fume concentrations in shipyard confined spaces. The training parameters demonstrated that total particulate concentrations are reduced, but more profoundly in the 90th percentile of the concentrations. This demonstrates a reduction in peak exposures so that workers are not being exposed to the very high concentrations typically seen in exposure modeling when the treatments are being introduced. Most of the adjustments concepts did result in a reduction of welding fume concentration and the training is valid.

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Appendix 1: Observation Form

Researcher:	Start:	End:	Date:	Shipyard:

WORK

1. **Ship name: ___________________**
2. **Shape of space**
   ☐ Simple ☐ Complex
3. **Type of job**
   ☐ New Construction ☐ Repair
4. **Type of space**
   ☐ Outside ***If Outside → Skip to6*** ☐ Partially enclosed space ☐ Confined space
   ☐ Exterior of vessel ☐ Enclosed space
5. **Enclosed space dimensions**
   Height ______ ft Length ______ ft Width ______ ft
6. **Number of other workers in space ______**
7. **Number of other welders in space ______**

EXHAUST VENTILATION

8. **How many blowers exhausting in the space ______**
   If 0 → skip to 17

9. **Exhaust duct 1 effectiveness?**
   air velocity______________
   duct diameter (in.)________
   ☐ High
   ☐ Medium
   ☐ Low
   ☐ Zero
10. **Proximity of exhaust duct 1 to high concentration area?**
   ☐ Local exhaust
   ☐ Regional exhaust
   ☐ General exhaust
11. **Height of duct opening relative to weld**
   ☐ Above
   ☐ Even
   ☐ Below
12. **Exhaust duct 2 effectiveness?**
   air velocity______________
   duct diameter (in.)________
   ☐ High
   ☐ Medium
   ☐ Low
   ☐ Zero
   ☐ Not present ***if Not Present, → skip to 17***
13. **Proximity of exhaust duct 2 to high concentration area?**
   ☐ Local exhaust
   ☐ Regional exhaust
   ☐ General exhaust
14. **Height of duct opening relative to weld**
   ☐ Above
   ☐ Even
   ☐ Below

15. Exhaust duct 3 effectiveness? **air velocity______________** **duct diameter (in.)________**	☐ High ☐ Medium ☐ Low ☐ Zero ☐ Not present ***if Not Present, → skip to 17***
16. Proximity of exhaust duct 3 to high concentration area?	☐ Local exhaust ☐ Regional exhaust ☐ General exhaust
17. Height of duct opening relative to weld	☐ Above ☐ Even ☐ Below
DILUTION VENTILATION	
18. How many blowers supplying the space	_______ ***if 0 → skip to 21***
19. Supply blower 1 effectiveness **air velocity______________** **duct diameter (in.)________**	☐ High ☐ Medium ☐ Low ☐ Zero
20. Supply blower 2 effectiveness **air velocity______________** **duct diameter (in.)________**	☐ High ☐ Medium ☐ Low ☐ Zero ☐ Not present ***if Not Present, → skip to 21***
21. Supply blower 3 effectiveness **air velocity______________** **duct diameter (in.)________**	☐ High ☐ Medium ☐ Low ☐ Zero ☐ Not present
MIXING AND CROSSDRAFT	
22. How is room being mixed?	☐ Supply blower ☐ Separate box/mixing fan ☐ Natural ☐ Other ☐ Not mixed
23. Room mixing?	☐ Appropriate (mixed or unmixed) ☐ Inappropriate (mixed or unmixed)
24. How is crossdraft generated?	☐ Minifan ☐ Supply blower ☐ Separate box/mixing fan ☐ Natural ventilation ☐ No Crossdraft **if No crossdraft, skip to 25**
25. Crossdraft at welder?	☐ Effective ☐ Partially Effective

26.	**Is work performed in dead space?**	☐ Yes ☐ No
27.	**Are exhaust & supply collocated?**	☐ Yes ☐ No
28.	**Supply air drawn from area free of air contaminants?**	☐ Yes ☐ No
29.	**Proximity of welder's head to plume?**	☐ Away from plume ☐ Near plume ☐ In plume
RESPIRATOR		
30.	**Respirator used?**	☐ Yes ☐ No ***if 0 → skip to 32*** ☐ Unsure ***if unsure → skip to 32***
31.	**Type of respirator used?**	☐ Air purifying – half mask ☐ Air purifying – full-face ☐ Powered air purifying ☐ Supplied air ☐ Disposable
32.	**Apparent respirator fit?**	☐ Poor ☐ Good ☐ Unsure
NEARBY WORKERS		
33.	**Is ventilation increasing exposure for other workers in space?**	☐ No ☐ Yes ☐ Unsure
TOTAL SCORE		**(SUM OF ABOVE)** __________

34. Type of work performed

☐ Welding or Hot Cutting	☐ Chipping/scaling	☐Fire watch or supervision
☐ Grinding	☐ Prep work or other no-exposure work	☐Other (please list): ______________________________
☐ Fitting/tacking		

35. Welding method used

☐ Stick (SMAW)	☐ MIG (GMAW)	☐ Carbon arc cutting (scarfing/gouging)
☐ TIG (GTAW)	☐ Flux core (Dual)	☐ Oxyacetylene
☐ Not Sure	☐ Flux core (Inner)	☐ Other __________

36.	**Overall, rate the effectiveness of the ventilation in the spacegiven the welding fume exposure in the space.**	☐High ☐ Medium ☐ Low ☐ Not present
37.	**Minutes welding during observation (e.g. 6/11)** ___________	