Characterization of Work Practices and Ventilation Techniques in Shipyard Confined Space Welding

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A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington
2012

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Program Authorized to Offer Degree:
Public Health—Environmental and Occupational Health Sciences

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ACKNOWLEDGEMENTS

Funding and support for this project has been provided by the National Institute for Occupational Safety and Health grant R01 0H 009655

Additional support from US Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health ERC grant 5T42 OH 008433.

CHAPTER I: INTRODUCTION AND BACKGROUND

Background

Welding fume health effects

Welding and thermal cutting processes generate fume and gases that can contain a variety of potentially dangerous air contaminants. The specific constituents of welding fume depend primarily on the welding processes used. For consumable welding processes, the electrode contributes the largest fraction of the mass present in the welding fume, however, materials from the base metal, electrode coating, shielding gases, and any surface coatings also may be present in the fume. Other factors that influence the rate and composition of welding fume include the welding speed, power supply voltage, wire feed speed, and arc length (Hovde & Raynor, 2007). Depending on the welding process used, welders can be exposed to metals in fume such as manganese, iron, aluminum, lead, nickel, copper, chromium, arsenic and zinc (AWS, 1979). Additionally, arc welders can be exposed to toxic gases, such as ozone, carbon monoxide, nitrogen oxide, and nitrogen dioxide (Antonini, 2003). Table 1 summarizes some of the common hazardous welding fume particulate and gaseous components.

A variety of adverse health effects resulting from exposure to welding fume are known. Acute effects, such as metal fume fever caused by inhalation of metal oxides produced during welding operations, have been well documented (Mueller & Seger, 1998). Epidemiologic studies have demonstrated that chronic pulmonary detriments such as bronchitis, fibrosis, wheezing, and decreased lung function are more common among welders when compared to control populations (Barhad et al., 1975). One such study, which documented chronic bronchitis and decreased lung function in mild steel welders, found time spent welding in confined spaces to be the main risk factor for development of those conditions (Bradshaw et al., 1998).

Table 1.1 Common welding particulate and gaseous contaminants

Particulates	Potential health hazard
Aluminum	Respiratory irritant
Beryllium	Damage to respiratory tract, established carcinogen
Cadmium	Respiratory irritation, pulmonary edema, potential carcinogen
Chromium, Hexavalent	Respiratory irritation, perforation of nasal septum, lung cancer
Copper	Respiratory irritation, metal fume fever
Iron Oxide	Siderosis, acute irritation to respiratory system
Lead (Inorganic)	Central nervous system effects, effects to reproductive system
Manganese	Central nervous system effects, metal fume fever
Molybdenum	Acute irritation of eye, nose, and throat
Nickel	Irritation, pneumonitis, pulmonary carcinogen
Vanadium	Acute irritation of eyes and throat, chronic bronchitis
Zinc Oxide	Metal fume fever

Gases	Potential health hazard
Carbon Monoxide	Headaches, dizziness, asphyxiation
Hydrogen Fluoride	Irritation to eyes, nose, and throat; bone damage
Nitrogen Oxides	Respiratory irritation and pulmonary edema
Ozone	Respiratory irritation and pulmonary edema
Phosgene	Respiratory irritation

*Source: Antonin, 2003

An association between welding fume exposure and lung cancer also has been suggested. Both nickel and chromium, which are emitted during stainless steel welding, are classified as human carcinogens (IARC, 1990). A study that evaluated incidence of pulmonary tumors in a cohort of stainless steel welders found a significant increase in death due to lung cancer in highly exposed welders, suggesting stainless steel welding fume containing nickel oxides and hexavalent chromium might be associated with increased cancer risk (Sjögren et al., 1987). A review of the welding fume health effects literature, however, concluded that a definitive link between non-stainless steel welding fume exposure and cancer has not been established (Antonini, 2003).

Despite a suggested increase of cancer risks from the epidemiologic evidence, the association is often uncertain due to potential confounding due to unknown subject smoking status, exposure to other carcinogens, and exposure misclassification (Antonini, 2003; Becker et al., 1985).

Long-term exposure to metals in welding fume, particularly manganese, may cause central nervous system effects. A case-control study that compared mild-steel shipyard welders to shipyard mechanics not exposed to welding fume found that manganese exposure was associated with abnormal function on neurological exams (Halatek et al., 2005). In another study, investigators found that welders exposed to manganese performed worse on tests of verbal learning, working memory, cognitive flexibility, and motor efficiency when compared to a control group. Additionally, the authors noted that this effect increased with reported hours spent welding (Bower et al., 2003). In addition to reduced cognitive function, there is concern that exposure to manganese in welding fume may increase the risk of development of Parkinsonism (Lucchini et al., 2007). A case-control study of 15 career welders that had been diagnosed with Parkinsonism concluded that the significantly earlier onset of disease in the cases when compared to the controls suggested that exposure to welding fume may be a risk factor for the disease (Racette et al., 2001).

Shipyard welding fume exposures

Welding in shipyards can be characterized by dynamic work in a constantly changing work environment. Unlike other station-based welding tasks, shipyard workers are employed under conditions similar to the construction industry, and must perform welds under a variety of work spaces that make it difficult to properly implement engineering controls, such as ventilation. In addition, shipyard welders routinely work in confined and enclosed spaces, such as storage tanks and bulkheads, that tend to restrict natural air movement and increase exposures to welding fume.

A literature review identified several studies that have characterized welding fume exposures in shipyard welders, all of which found exposures that consistently exceeded occupational exposure limits for welding fume and various constituent metals. One such study reported total welding fume and hexavalent chromium breathing zone concentrations in enclosed spaces inside ships and in welding shops (Karlsen et al., 1994). The study found that during stainless steel welding tasks total particulate exposures ranged from 0.3 to 29 mg/m^3 in enclosed spaces aboard ships, compared to 0.5 to 6.6 mg/m^3 in the welding shops. In another study, investigators found similar results for total air particulate breathing zone concentrations when comparing welding in confined spaces and welding shops (48-92 mg/m^3 and 6-36 mg/m^3, respectively) (Barhad et al., 1975). In a hexavalent chromium exposure assessment, the authors reported mean concentrations of 6.2, 12 and 140 $\mu g/m^3$ for an offshore module, welding shop and confined space, respectively (Karlsen et al., 1994). In both studies, investigators reported exposures that exceed Washington State PEL (Permissible Exposure Limits) for both total welding fume and hexavalent chromium (5 mg/m^3 and 5 $\mu g/m^3$, respectively) (WAC, 2007).

Determinants of exposure

There are more than 80 different types of welding processes used, each with specific advantages and applications (EPA, 1995). Some of the most common hot work processes used in ship building and repair are: shielded metal arc welding (SMAW or "stick welding"), flux core arc welding (FCAW), gas metal arc welding (GMAW or "MIG"), gas tungsten arc welding (GTAW or "TIG"), oxyfuel gas welding (OFW or typically "oxyacetylene welding"), oxyfuel gas cutting (OFC or "torch cutting"), and carbon arc cutting ("scarfing") (Harris 2002). Fume composition and generation rates vary widely between welding processes. In general, approximate fume generation rates are highest for FCAW welding operations, followed by GMAW, SMAW and GTAW (AWS, 1979). Specific fume composition is also dependent on the welding process employed; therefore recommended fume control methods should consider the type of work and welding process performed.

Although fume generation depends on the welding type, several studies indicate that other factors, such as the type of space and ventilation techniques employed, are also important determinants of exposure (Flynn and Susi, 2010; Liu et al., 2011; Hobson et al., 2011). In one such study, investigators performed a regression analysis of total particulate and manganese air measurements compiled from various welding exposure assessment studies, and found that the degree of enclosure of the work space and use of local exhaust ventilation were the most important determinants of exposure (Lie et al., 2011).

Ventilation methods

Currently there are no specific ventilation guidelines for welding performed in the shipyard industry, other than the general requirement that the ventilation must be “of sufficient capacity and so arranged as to produce the number of air changes necessary to maintain welding fume and smoke within safe limits” (OSHA, 2002). However, welders in shipyards are subject to federal OSHA regulations [29 CFR 1910.252 (General Industry Subpart Q: Welding, Cutting, and Brazing) and 29 CFR 1926.353 (Construction Subpart J: Welding and Cutting], which require ventilation in enclosed or confined spaces be: (1) at a minimum of 2000 ft^3/min of airflow for each worker in spaces that have a volume less than 10,000 ft^3, or (2) local exhaust devices capable of maintaining 100 ft/min of airflow at the point of fume generation in the direction of the exhaust intake (OSHA, 1993; OSHA, 2009). These regulations outline the two widely used ventilation techniques for the control of welding fume in enclosed and confined spaces: (1) general dilution ventilation (GDV) and (2) local exhaust ventilation (LEV).

In the context of the control of welding fume exposures, LEV captures fume near the weld, usually with a flexible and portable exhaust duct, and removes it from the space before it can be inhaled. GDV, on the other hand, reduces fume concentration available to inhale by diluting the space with large amounts of fresh air to mix the air in the space. An obvious disadvantage to GDV is that there is little control over the direction of the airflow. This lack of control combined with the variable position of the welder can result in inefficient dilution of fume from the worker’s breathing zone (Bowes et al., 1993). In contrast to GDV, the use of LEV allows the user more control over the removal of fume and , when implemented correctly, removes fume before it builds up to above acceptable levels.

Several experimental evaluations of the use of ventilation in enclosed and confined space welding tasks have been performed. In one study on the relative effectiveness of GDV and LEV in a hypothetical shipyard welding scenario, investigators performed a controlled experiment with trained SMAW welders in the bulkhead of a ship (Wurzelbacker et al., 2010). Overall, total particulate breathing zone concentrations using the LEV method were 50% of the exposure measured under the GDV configuration. Another study evaluated the effectiveness of LEV to control mild-steel welding fume in a partially enclosed experimental space and found the use of LEV reduced personal breathing zone exposures to total fume and manganese by up to 75% when compared to no ventilation, but that the effectiveness was greatly dependent on work practices, such as the proximity and vertical location to of the exhaust intake relative to the weld (Meeker et al., 2007). In a similar follow-up study the same investigators concluded that when placed within 1.5 duct diameters and above the weld, LEV was effective at keeping breathing zone concentrations of hexavalent chromium below the NIOSH REL (1 µg/m^3) (Meeker et al., 2010). Only one study that evaluated the effectiveness of GDV in an experimental setting was identified in the literature (Harris et al., 2007). That controlled experiment looked at manganese exposures during SMAW welding in enclosed spaces and found that generational dilution ventilation, even when in excess of 2000 ft^3/min in a space with a volume of 2200 ft^3 (equating to an airflow rate of roughly four times the OSHA recommended general dilution ventilation rate for enclosed spaces), may not be adequate for maintaining exposures below acceptable limits for the welder and others present in the room.

Other assessments have focused on the use of ventilation to control welding fume in real-world enclosed and confined spaces. In one study, Susi *el al.* (2000) analyzed 200 breathing zone measurements of total fume particulate from boilermakers, pipefitters, and ironworkers. When stratified by type of ventilation, they found that both LEV and GDV effectively reduced breathing zone concentrations (1.99 mg/m^3 and 1.72 mg/m^3, respectively) when compared to natural ventilation (5.39 mg/m^3) and no ventilation (9.45 mg/m^3). While GDV and LEV performed similarly, the authors noted that the effective control of fume with GDV was highly variable and dependent on the size, configuration, and degree of enclose of the space (Flynn & Susi, 2010). A literature review publication on the use of LEV in construction by the same authors describes several shipyard LEV-welding studies (Flynn & Susi, 2011). Two US Navy assessments of exposure to constituent metals in welding fume reported that the use of fume extraction guns (a type of LEV that is attached to the terminal end of the welding nozzle) was the most effective ventilation method observed, followed by a combination of LEV and GDV, then by general exhaust ventilation (GEV, placement of an exhaust duct in the space but not close to the source of generation) (US Department of Navy as cited in Flynn & Susi, 2011). In another shipyard ventilation study Harris (2000) reported that the use of LEV reduced hexavalent chromium exposures during stainless steel welding in open, enclosed, and confined spaces. Consistent with other findings, however, the effectiveness of the LEV was greatly depending on the proper placement of the exhaust intake by the operator.

The majority of published recommended guidelines for the effective ventilation of hot work exposures in enclosed and confined spaces recommend LEV as the preferred method (Harris et al., 1996; AWS, 1979). As previously discussed, the appropriate capture of contaminated air with LEV depends greatly on the proper placement of the exhaust intake. The ACGIH industrial ventilation guidelines recommend an acceptable capture velocity at the source of emission to be between 100 and 200 ft/min; noting that velocities below 100 ft/min would be ineffective at capturing generated fume, and velocities above 200 ft/min may disturb the shielding gas for arc welding processes and affect weld quality (ACGIH, 2010). The primary limitation of LEV is that the exhaust intake must be placed very close to the weld in order to capture the fume generated.

The capture velocity equation for an exhaust duct with a plain circular opening is:

$$V_C = \frac{0.1Q}{(x^2 + 0.1A)}$$

Where V_C is the capture velocity (in ft/min) at x distance away (in ft) from the exhaust intake, and A is the area of the intake opening (in ft^2) (ACGIH, 2010). Note that the capture velocity decreases with the square of the distance from the exhaust intake, resulting in significant losses of fume capture potential as the exhaust is moved away from the generation source. To illustrate this effect we can consider a flexible exhaust duct with a diameter of 8 inches (a common duct size for use in shipyard ventilation) that is placed one duct diameter away from a weld. In order to maintain the minimum capture velocity of 100 ft/min the airflow at the exhaust intake opening would have to be 1373 ft/min, a typical and achievable velocity given standard ventilation equipment available to shipyard welders. As the distance between the weld and the exhaust duct increases, however, the capture velocity drops off rapidly. Assuming the same airflow through the exhaust duct, the capture velocity would drop off to an ineffective 26 ft/min at two duct diameters away from the weld (16 inches), and to an imperceptible 12 ft/min at three duct diameters away from the weld (24 inches).

Shipyard ventilation project

The work conducted towards this thesis was part of a larger shipyard ventilation study. Recognizing that current ventilation strategies employed in shipyards are often not sufficient at controlling exposure to welding fume, the overall study sought to do the following:

1. Develop a set of general ventilation guidelines that could be practically implemented
2. Teach those guidelines to shipyard welders using training intervention
3. Evaluate the adoption of those guidelines

This thesis describes work that has been accomplished towards aims 1 and 3.

Chapter II describes controlled ventilation experiments that were completed to gain further insight into the factors that affect successful ventilation of enclosed and confined spaces. The initial shipyard ventilation study procedure called for the evaluation of ventilation techniques to be performed on real-work shipyard welders. The practicality of such assessments, however, proved to be impossible, primarily due to the limited opportunity to vary key ventilation and work practice parameters so that meaningful comparisons could be made. Instead, these factors were assessed in a controlled experimental confined space.

Recognizing that the effective use of ventilation in a controlled experimental space would not directly translate to real-world practice, the principle aim of the experiments was to compare broad ventilation techniques. Results from the ventilation experiments were used to inform the development of the training intervention guidelines as well as to inform interpretation of the baseline observations performed on actual shipyard welding tasks.

Chapter III describes a baseline survey of shipyard welder work practices use of ventilation at a Seattle shipyard. Over a five month sampling period, enclosed and confined space welding tasks were characterized using an observational tool that was developed based on the recommended ventilation guidelines. Generally, the aims of the baseline shipyard observations were to identify common ventilation challenges encountered by shipyard welders, to explore the relationship between the current use of recommended practices and welding fume exposure, and to evaluate the use of the observation tool to determine how it can assess the effectiveness of the training.

Lastly, the discussion and conclusion sections of Chapter III summarize the successes and main conclusions of this thesis in relation to the goals of the shipyard ventilation study, identify challenges encountered, and make recommendations for future study efforts.

CHAPTER II: CONTROLLED VENTILATION EXPERIMENTS

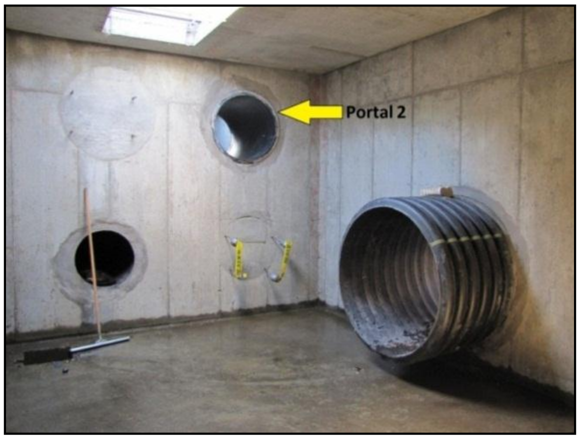
Ventilation experiments were conducted in a controlled space to further compare ventilation techniques for welding fume control. In addition to type of ventilation, the following parameters were evaluated: position of the weld, vertical location relative to the weld, welding in a dead air space creating by short-circuiting of airflow, general area mixing of the space, and a cross draft created across the welder's breathing zone.

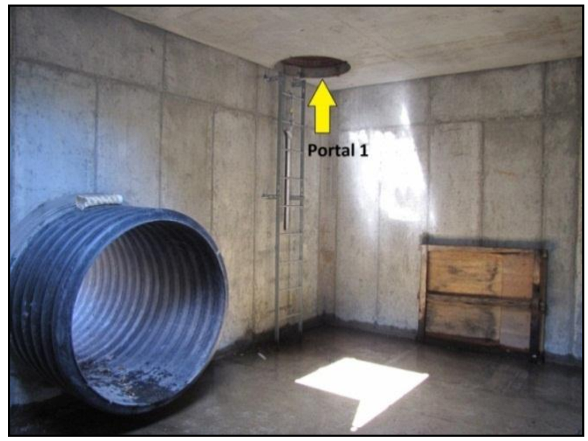
Insights gained from the experimental results were used to further develop the recommended ventilation guidelines for inclusion in the shipyard welding intervention training, and to inform the development and interpretation of the observational form used to characterize use of ventilation during real-world shipyard welding tasks. The experiments were completed by researchers and a volunteer welder over four days in June, 2011.

Methods

Experimental Space

An experimental space with a simple box geometry and at least two openings was sought to conduct the controlled experiments. A concrete vault at the City of Seattle Joint Training Facility was chosen and experiments were carried out with the approval and cooperation of the Seattle Fire Department. The vault, which is normally used for simulated confined space entry and rescue training, measured 18 feet long, 12 feet wide, and 10 feet high. Two openings in the space were utilized for ventilating the space; all remaining openings in the space were sealed from the inside with plastic sheeting. The first opening, "Portal 1", was an open manhole with a diameter of 1.5 feet and was located on the ceiling in the southwest corner of the space that opened to the outdoor environment (Figure 2.1). Portal 1 was used as the entry point for the ventilation duct to the space and was sealed around the duct with plastic sheeting to prevent air exchange around the duct. The second opening, "Portal 2", was a tunnel terminus to the space that had a diameter of approximately 2.5 feet. The middle of the opening was located 7 feet high on the northern side of the west wall and connected to a tunnel that ran west approximately 6 feet before opening up to another smaller vault that was open to the fresh air on top by way of another manhole cover (Figure 2.2). Portal 2 served as the fresh make-up air supply point during exhaust scenarios and the point of exit for exhausted air during dilution scenarios. Figures 2.3 and 2.4 provide plan and elevation sketches of the experimental space.





Figures 2.1(left) and 2.2 (right). Location of Portal and Portal 2 within the experimental space facing the northwest and northeast corners, respectively

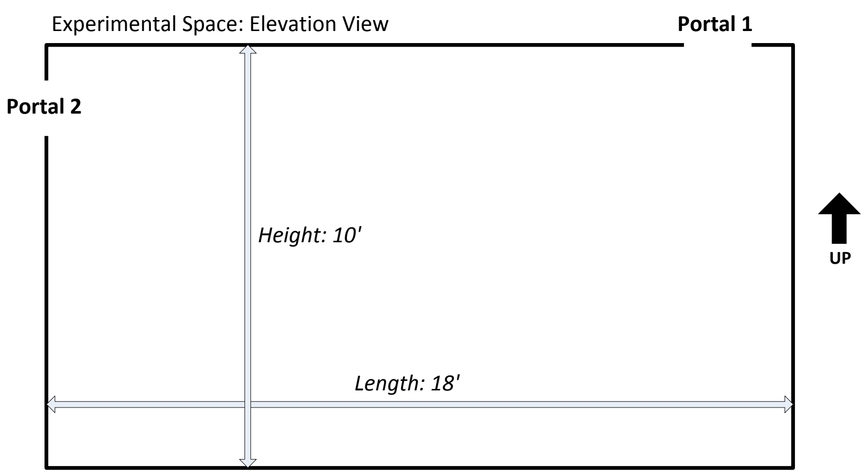


Figure 2.3. Elevation view of experimental space with relative locations of ventilation openings

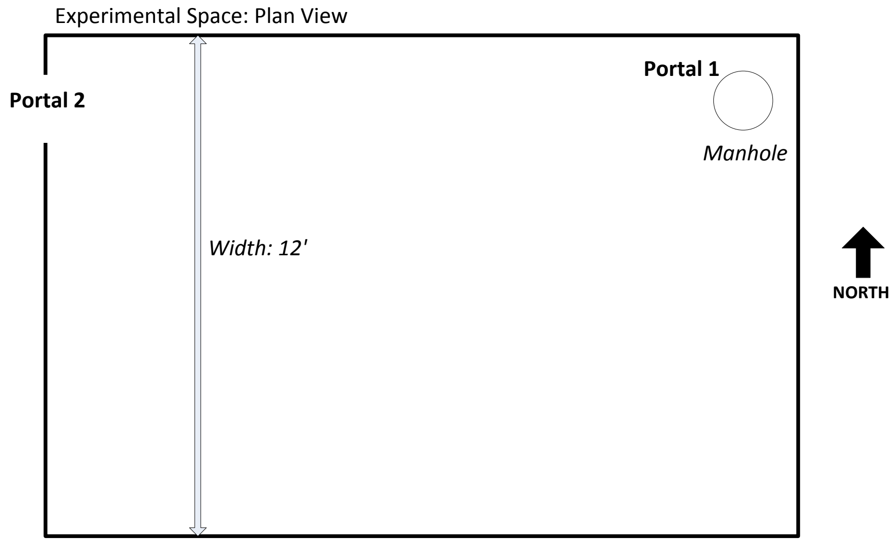


Figure 2.4. Plan view of experimental space with relative locations of ventilation openings

Experimental Scenario Evaluation

Fume Generation

Welding fume was generated using the shielded metal arc welding process (SMAW) for carbon steel with Excalibur® 7018 low hydrogen stick electrodes (4 mm diameter). Power was provided by a Miller Trailblazer® 275DC engine driven welder/generator set to supply constant current at the “soft stick” preset arc-force setting. For each welding scenario, a trained welder volunteer welded by making repeated horizontal passes on a small piece of mild steel. To limit the variability in mass generation associated with sporadic arc time, the operator welded continuously until the entire electrode was consumed, making an effort to maintain consistent welding speed.

Fume Concentration Measurement

The effectiveness of welding fume control for each ventilation scenario was evaluated by measuring total particulate concentrations at four locations within the space. Total particulate concentrations were measured in milligrams per cubic meter with MIE Personal DataRAM™ pDR-1200 particulate monitors configured to sample in active mode at 10-second-average logging intervals. Air was drawn through each pDR sampling chamber by attaching a SKC

AirChek XR5000 personal air sampling pump to the monitor outlet port. Personal sampling pumps were calibrated to 2.0 liters per minute using a Bios Defender™ primary standard flow meter. A two-foot section of flexible PVC tubing was attached to the inlet port on each pDR monitor and the terminal end of the tubing was placed in the sampling location of interest. To ensure acceptable agreement between the four pDR monitors, side-by-side comparisons were made by measuring aerosol concentrations in a controlled laboratory chamber before, during and after the ventilation experiments were conducted. All pDR monitors measured particulate concentrations within five percent of each other, with the exception of a rental unit that was used on three of the four experimental days. Adjustments of experimental concentration data from the rental pDR were made using a linear regression equation determined by comparing real-time concentration data from the rental pDR to the mean real-time values of the other three monitors in the laboratory chamber. Appendix A describes the pDR comparison data in greater detail. The calibration of each pDR was checked before each sampling day by performing the internal span check ("zeroing") procedure specified in the instrument user instruction manual.

For each experimental scenario, pDR monitors sampled air in the following locations:

1. "Breathing Zone pDR":
    - The terminal end of the Breathing Zone pDR sampling tube was attached to the lapel of the welder's jacket just under the collar bone.
2. "Exhaust pDR"
    - The terminal end of the Exhaust pDR sampling tube was suspending in the middle of the exhaust portal approximately 2.5 portal diameters downstream from the end open to the experimental space.
        - For scenarios where air was mechanically exhausted from the space, the Exhaust pDR sampled in the flexible exhaust ducting place at some location in the space.
        - For dilution scenarios the Exhaust pDR was placed in Portal 2, which served as the point at which contaminated air was forced out of the space.

3. "High pDR"
    - The terminal end of the High pDR sampling tube was placed at the ceiling of the space in the middle of the room.
4. "Low pDR"
    - The terminal end of the Low pDR sampling tube was placed at the floor of the space in the middle of the room.

Ventilation

A number of different types of ventilation equipment were utilized in the experiments. The exact use of each ventilation component by scenario is detailed in the next section; however, in general, the ventilation equipment provided the following types of ventilation to the space: (1) mechanical exhaust ventilation, (2) mechanical dilution ventilation, (3) area mixing, and (4) breathing zone cross-draft ventilation. Table 2 provides a list of the ventilation equipment used in the experiments (Figures 2.5-2.8).

Table 2.1. Controlled experiment ventilation equipment

Type	*Description*	*Use in experiments*
Axial Blower	Eramco RamRan UB20 confined space 120V blower	Airflow power source for mechanical exhaust and dilution
Centrifugal Blower	Lincoln Electric Mobielflex 100-NF 765 ft^3/min centrifugal fan	Area mixing
"Mini" fan	Caframo MiniMax Delux Model 737, battery operated variable speed fan	Breathing zone cross-draft airflow
Box fan	Lasko Weather Sheid™ 20 inch 3-speed box fan	Breathing zone cross-draft airflow
Flexible Ducting	12 inch diameter EkcoFlex confined space ventilation ducting (25 feet)	Positioning of mechanical exhaust and dilution ventilation (attached to axial blower)

Figure 2.5. Axial blower

Figure 2.6. Area Mixing Blower

Figure 2.7. “Mini” fan

Figure 2.8. Box Fan

Figure 2.9. Air Particulate “Scrubber”

The ventilation configuration for each experimental scenario was characterized by noting the exact location of each ventilation component in the space and recording those locations in a field sheet for each scenario configuration. In addition to the physical location of ventilation components, air flows were measured at the following locations: (a) Portal 2 (the point of exhaust for dilution scenarios and the source of make-up air for exhaust scenarios), (b) the terminal end of the flexible ventilation ducting mechanically exhaust or supplying air to the space, and at (3) any other mechanical ventilation source within the space, such as area mixing fans and cross draft fans. Air velocity measurements were performed with a TSI VelociCalc® 9565 Air Velocity Meter equipped with a rotating vane anemometer. For each source of airflow a 15-second traverse of the area of the ventilation face was performed and the average velocity over that interval was recorded as the airflow reading. For each scenario replicate the number of air changes per hour (ACH) in the space was computed by using the volumetric flow rate (Q) measured at the terminal end of the flexible ventilation duct in the space and dividing that by the volume of the space.

Experimental Scenarios

The ventilation experiments were conducted over four days in June, 2010. For each experimental day, triplicates of 4-7 different scenarios were conducted in sequence. For example, on Day One, Scenarios 1.1 through 1.5 were completed in sequence three times starting with Scenario 1.1. The following steps were performed for each scenario replicate:

1. Set up ventilation and welding equipment
2. Record space and ventilation characteristic data (supply, exhaust, and mixing air velocities, location of pDR monitors, location of ventilation equipment, location of welder)
3. Begin welding – record scenario “start” time
4. Stop welding – record time
5. Wait for space to purge – record scenario “stop” time
6. Reconfigure ventilation and welding for subsequent scenario

The purge period was determined by allowing the scenario ventilation configuration to ventilate the space unaltered until either the concentration analog read-out on each pDR in the space reported particulate concentrations less than 0.05 mg/m^3 or until ten minutes had passed since welding period had ended, whichever came first. After the purge period, an additional dilution blower was added to remove residual weld fume from the space. The subsequent scenario replicate was not initiated until all pDR concentrations dropped below 0.01 mg/m^3.

Scenario parameters were chosen in a way that would allow for the evaluation and comparison of the effectiveness of different ventilation techniques. In general, the following ventilation parameters were evaluated:

- Dilution ventilation vs. Exhaust Ventilation
- Vertical location of the ventilation duct relative to the weld
- Vertical position of the weld in the space
- Welding in a "dead space" (welding upstream versus downstream of the point of fresh air supply)
- Area air mixing
- Breathing zone cross-draft air flow
- Proximity and vertical placement of exhaust ventilation

In the first day of experiments the effectiveness of general exhaust ventilation (GEV) was evaluated. For the reference GEV scenario (Scenario 1.1), welding was performed on the middle of the west wall inside the space. Air was exhausted from the space by placing the exhaust duct in the middle of the space behind the welder. The duct exited the space through Portal 1 and was connected to the axial blower which was located outside the space; the space surrounding the duct in Portal 1 was sealed with plastic sheeting to force make-up air to enter the space through Portal 2. Subsequent Day One scenarios repositioned the weld and the exhaust duct. For example, Scenarios 1.2 and Scenario 1.3 moved the location of the weld to the ceiling and to the floor, respectively, while maintain the central positioning of the GEV duct. Similarly, Scenarios 1.4 and 1.5 varied the location of the exhaust duct by moving it to the ceiling and to the floor, respectively, while maintaining the weld at the center of the west wall.

Day Two of the ventilation experiments evaluated general dilution ventilation (GDV) using the same approach used in Day One. The GDV reference scenario (2.1), for example, was configured identically to the GEV reference scenario (1.1), except that the flow through the ventilation duct was reversed in order to mechanically supply air to the space I the direction of the welder. Subsequent Day Two scenarios evaluated the vertical positioning of the weld and ventilation in the same manner as with GEV, moving the weld to the ceiling and floor (2.2 and 2.3, respectively), and moving the dilution ventilation duct to ceiling and floor (2.4 and 2.5, respectively).

Day Three of the ventilation experiments evaluated what effect welding in a ventilation "dead space" created by short circuiting of the relative positioning of supply and exhaust points within the space. To do so, a "Short Circuit" Dilution Ventilation (SCD) reference scenario (3.1) was performed in which the ventilation configuration was identical to that of the GDV reference scenario (2.1), but the weld was moved to the east wall of the space, a point that we hypothesized would be effected very little by airflow supplied by the ventilation duct in the middle of the room.

Additionally, the effectiveness of various air mixing techniques were investigated by applying area mixing (3.2, 3.5), area particulate "scrubbing" (3.6, 3.7), and breathing zone cross-draft air flow (3.3, 3.4, 3.5. 3.7) techniques to the SCD reference scenario.

In the final day of experimental sampling, Day Four, the effectiveness of exhaust ventilation intermediate to LEV and GEV was assessed, designated "Regional" Exhaust Ventilation (REV). Recognizing that the nature of shipyard work often makes the placement of LEV unfeasible, we sought to investigate what advantage placing an exhaust duct within several feet of the weld had over the placement of a GEV in the middle of the space. In the REV reference scenario (4.1), the weld was performed on the west wall consistent with the GEV reference scenario. The exhaust duct, however, was moved to approximately 2.5 feet of the weld; beyond the point at which it would be considered LEV. In subsequent Day Four scenarios, the effect of assisting the removal of fume with a breathing zone cross-draft (4.2), and moving the REV exhaust duct to a vertical position above the weld (4.3) was evaluated.

Table 2.2 summarizes the variables that were varied and the intended effects explored for each experimental scenario. Appendix B provides detailed plan and elevation sketches for each experimental scenario, providing relative placement of ventilation, the weld, and pDR monitors.

Table 2.2: Experimental scenarios- ventilation parameters varied and intended effects explored. Bold text indicates primary parameter altered in relation to comparison/reference scenarios.

Scenario #	*Scenario name*	*Type of ventilation*	*Vertical position of ventilation*	*Proximal location of ventilation*	*Vertical position of weld*	*Weld relative to ventilation air-flow*	*Space Mixing?*	*Breathing Zone Cross-draft*	*Particulate air "scrubbing"?*	*Primary comparison scenario*	*Intended effect explored*
1.1	GEV reference	**Exhaust**	Middle	General	Middle	In flow	No	No	No	2.1	Type of ventilation
1.2	GEV high weld	Exhaust	Middle	General	**High**	In flow	No	No	No	1.1, 1.3	Position of weld
1.3	GEV low weld	Exhaust	Middle	General	**Low**	In flow	No	No	No	1.1, 1.2	Postion of weld
1.4	High GEV	Exhaust	**High**	General	Middle	In flow	No	No	No	1.1, 1.5	Vertical position of exhaust
1.5	Low GEV	Exhaust	**Low**	General	Middle	In flow	No	No	No	1.1, 1.4	Vertical position of exhaust
2.1	GDV reference	**Dilution**	Middle	General	Middle	In flow	Yes	No	No	1.1	Type of ventilation
2.2	GDV high weld	Dilution	Middle	General	**High**	In flow	Yes	No	No	2.1, 2.3	Position of weld
2.3	GDV low weld	Dilution	Middle	General	**Low**	In flow	Yes	No	No	2.1, 2.2	Position of weld
2.4	High GDV	Dilution	**High**	General	Middle	In flow	Yes	No	No	2.1, 2.5	Vertical position of dilution
2.5	Low GDV	Dilution	**Low**	General	Middle	In flow	Yes	No	No	2.1, 2.4	Vertical position of dilution
3.1	SCD reference	Dilution	Middle	General	Middle	**Out of flow**	Yes	No	No	2.1	Welding in dead space
3.2	SCD + area mixing	Dilution	Middle	General	Middle	Out of flow	**Yes +**	No	No	3.1	Area mixing
3.3	SCD + cross-draft (high flow)	Dilution	Middle	General	Middle	Out of flow	Yes	**High flow**	No	3.1	BZ cross-draft
3.4	SCD + cross-draft (low flow)	Dilution	Middle	General	Middle	Out of flow	Yes	**Low flow**	No	3.1	BZ cross-draft
3.5	SCD + area mixing + cross-draft	Dilution	Middle	General	Middle	Out of flow	**Yes +**	**Low flow**	No	3.1, 3.2, 3.4	Area mixing + BZ cross-draft
3.6	SCD + air "scrubber"	Dilution	Middle	General	Middle	Out of flow	**Yes +**	No	**Yes**	3.2	Air "scrubbing"
3.7	SCD + air "scrubber" + cross-draft	Dilution	Middle	General	Middle	Out of flow	**Yes +**	**Low flow**	**Yes**	3.6, 3.4	Air "scrubbing" + BZ cross-draft
4.1	REV reference	Exhaust	Middle	**Regional**	Middle	In flow	No	No	No	1.1	Proximity of exhaust
4.2	REV + mini-fan cross-draft	Exhaust	Middle	**Regional**	Middle	In flow	No	**Low flow**	No	4.1	Mini-fan BZ cross-draft
4.3	High REV + mini-fan cross-draft	Exhaust	**High**	**Regional**	Middle	In flow	No	**Low flow**	No	4.2, 4.1	Vertical position of exhaust + BZ cross-draft

Data Analysis

Real-time particulate concentration data from each of the four pDR monitors was uploaded, matched according to time and organized by scenario replicate. The time that welding began for each scenario replicate was recorded as time zero, and total scenario time was truncated to 6 minutes for each replicate. Data was organized in Microsoft® Excel and coded by scenario, replicate, welding/not welding, type of ventilation, vertical position of ventilation relative to weld, weld position, presence of area mixing, presence of breathing zone cross flow, presence of area scrubbing, dead space welding, and proximity of ventilation relative to the weld. Additionally, volumetric flow rates for exhaust and supply portals were calculated using measured air velocities and matched to each replicate.

For each scenario replicate, the following comparison metrics were computed (Table 2.3):

1. Exposure:
    - Exposure was estimated by the concentration measured in the welder's breathing zone with the Breathing Zone pDR.
    - Additionally, the potential for secondary "area" space exposures was estimated by calculating the "average" area concentration, which was equal to the average of the High and Low pDRs. Under this approach it was assumed that a secondary exposure had an equal opportunity of occurring at any point within the space.
2. Area Mixing:
    - Area mixing was estimated by assessing the extent of vertical stratification of welding fume in the space. This was accomplished by calculating a "vertical mixing" ratio that compared the fume concentrations measured with the High and Low pDRs.
3. Fume Removal Efficiency:
    - The ability for a given ventilation scenario to remove welding fume from the space was estimated by calculating an average fume mass removal rate, equal to the average mass of total particulate removed at the exhaust point each second.

Table 2.3. Scenario fume comparison metrics

Metric	*Equation*	*Unit*
Welder's exposure =	[Mean Breathing Zone pDR conc.]	mg/m^3
Area exposure =	[Mean High pDR conc. + Mean Low pDR conc.] / 2	mg/m^3
Area mixing =	[Mean High pDR conc.] / [Mean Low pDR conc.]	Unit-less
Fume removal efficiency =	[Mean Exhaust pDR conc.] x [Exhaust volumetric flow rate (in m^3/sec)]	mg/sec

Scenario comparison metrics were computed for each scenario triplicate and compiled in the following two Excel (Microsoft, Redmond WA) datasets: (a) Raw 10-seond average concentration data, matched by time and coded by scenario replicate, and (b) Average of 3-secenario replicate concentrations, matched by scenario and organized by total, weld, and purge periods. The datasets were then uploaded and analyzed in Stata 12 (StataCorp, College Station, TX).

Results

Average values of welder's exposure, area exposure, area mixing, and fume removal metrics were compared across all experimental scenarios (Table 2.4)

<u>General Exhaust versus General Dilution</u>

The effectiveness of exhaust versus dilution ventilation was assessed by comparing the two scenarios where the only parameter that varied was the type of ventilation: the GEV Reference scenario and the GDV Reference scenario (1.1 and 2.1). Figures 2.10-2.17 show schematics of the Scenario 1.1 and Scenario 2.1 configurations, real-time concentration plots, and comparison figures for welder's exposure, area exposure, vertical mixing, and fume removal metrics.

Table 2.4. Average comparison metrics for each experimental scenario calculated for total, weld, and period times (n = 3 for all scenarios)

Scenario		**Welder's exposure (mg/m^3)**						**Area exposure (mg/m^3)**						**Area mixing (ratio)**						**Fume removal (mg/sec)**					
		Total		Weld		Purge		Total		Weld		Purge		Total		Weld		Purge		Total		Weld		Purge	
#	Name	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*	μ	*SD*
1.1	*GEV reference*	1.5	0.3	0.3	0.2	1.9	0.4	3.2	0.8	2.5	0.5	3.5	1.1	3.7	0.5	5.3	1.3	3.3	0.6	1.2	0.2	0.5	0.0	1.5	0.3
1.2	*GEV high weld*	2.2	0.6	0.9	0.7	2.6	0.8	5.4	1.4	4.3	1.4	5.9	2.1	8.7	2.3	45.3	12.1	6.8	2.9	1.3	0.1	0.7	0.6	1.6	0.1
1.3	*GEV low weld*	1.6	0.2	0.9	0.4	1.9	0.3	2.6	0.3	2.2	0.3	2.9	0.4	2.0	0.6	2.4	1.2	2.0	0.6	1.2	0.2	0.8	0.4	1.4	0.1
1.4	*High GEV*	1.1	0.3	0.2	0.1	1.4	0.3	2.0	0.3	1.7	1.1	2.1	0.1	2.6	1.2	4.3	3.0	2.2	0.8	1.3	0.1	0.9	0.3	1.5	0.1
1.5	*Low GEV*	1.6	0.2	0.3	0.1	2.1	0.3	2.8	0.7	2.5	1.2	2.9	0.6	2.4	0.5	5.3	2.7	2.1	0.6	1.1	0.2	0.5	0.1	1.3	0.1
2.1	*GDV reference*	1.2	0.5	1.8	0.8	1.0	0.3	1.2	0.4	1.5	0.4	1.1	0.4	0.9	0.1	0.7	0.3	0.9	0.1	0.9	0.2	1.4	0.7	0.7	0.2
2.2	*GDV high weld*	1.2	0.2	1.7	0.4	1.0	0.2	1.4	0.4	2.4	0.9	1.1	0.3	2.0	0.8	6.1	3.3	1.1	0.1	0.8	0.1	1.2	0.3	0.6	0.1
2.3	*GDV low weld*	2.5	1.5	7.3	6.0	0.9	0.2	1.1	0.1	1.4	0.3	1.0	0.1	0.9	0.2	0.8	0.4	1.0	0.1	0.8	0.2	1.3	0.8	0.7	0.0
2.4	*High GDV*	1.8	0.4	5.4	1.5	0.7	0.2	0.8	0.2	0.9	0.1	0.8	0.2	1.3	0.1	2.0	0.2	1.1	0.1	0.8	0.1	1.6	0.6	0.5	0.1
2.5	*Low GDV*	0.8	0.3	1.6	1.0	0.6	0.2	0.8	0.2	1.2	0.4	0.7	0.2	1.3	0.4	3.1	2.1	0.9	0.1	0.8	0.0	2.0	0.2	0.4	0.1
3.1	*SCD reference*	2.5	0.5	5.0	2.2	1.6	0.1	1.7	0.1	1.1	0.1	1.9	0.1	1.2	0.1	2.2	0.5	1.1	0.1	0.9	0.2	0.6	0.3	0.9	0.1
3.2	*SCD + area mixing*	1.8	0.8	2.9	1.0	1.4	0.6	1.6	0.5	1.5	0.4	1.6	0.6	0.9	0.2	1.0	0.4	0.9	0.1	0.8	0.1	0.8	0.1	0.8	0.2
3.3	*SCD + cross-draft (high flow)*	1.3	0.2	1.7	0.2	1.2	0.2	1.4	0.1	1.3	0.1	1.4	0.2	1.1	0.1	1.5	0.3	1.1	0.1	0.7	0.0	0.6	0.0	0.7	0.1
3.4	*SCD + cross-draft (low flow)*	1.7	0.2	1.7	0.5	1.7	0.1	1.7	0.2	1.4	0.1	1.9	0.2	1.2	0.1	2.1	0.9	1.1	0.0	0.8	0.1	0.5	0.1	0.8	0.1
3.5	*SCD + area mixing + cross-draft*	1.4	0.1	2.1	0.2	1.2	0.1	1.3	0.0	1.3	0.1	1.4	0.1	1.1	0.1	1.1	0.0	1.0	0.0	0.7	0.0	0.9	0.1	0.7	0.0
3.6	*SCD + air "scrubber"*	2.2	0.6	5.1	1.7	1.1	0.1	1.5	0.1	1.6	0.2	1.4	0.2	1.2	0.1	1.5	0.0	1.1	0.1	0.7	0.1	0.7	0.1	0.7	0.1
3.7	*SCD + air "scrubber" + cross-draft*	1.0	0.1	1.3	0.2	0.9	0.1	1.4	0.1	1.7	0.1	1.2	0.1	1.4	0.0	2.1	0.2	1.1	0.0	0.7	0.0	0.7	0.1	0.6	0.1
4.1	*REV reference*	1.7	0.2	1.0	0.2	2.0	0.2	2.5	0.5	1.7	1.0	2.9	0.4	2.1	0.5	4.3	3.6	1.8	0.1	1.1	0.1	0.6	0.4	1.4	0.1
4.2	*REV + mini-fan cross-draft*	1.3	0.1	0.6	0.2	1.6	0.2	2.6	0.0	2.4	0.6	2.7	0.2	2.6	0.2	6.7	2.5	2.0	0.4	1.1	0.1	0.7	0.2	1.2	0.1
4.3	*High REV + mini-fan cross-draft*	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	1.3	0.4	2.0	.	1.2	0.2	0.9	0.1	2.5	0.3	0.1	0.1

Exposure

There was little difference in the average breathing zone concentration between GEV and GDV when comparing exposure for the entire scenario time (1.47 mg/m^3 and 1.20 mg/m^3, respectively). However, the real-time concentration plots show that the modes for peak breathing zone concentrations differ. In the GEV scenario, very little exposure actually occurs during the weld period (0.31 mg/m^3) compared to the purge period (1.92 mg/m^3). Conversely, for the GDV scenario, the average breathing zone concentration is higher during the weld period (1.82 mg/m^3) when compared to the purge period (1.00 mg/m^3) (Figure 2.14).

The potential for secondary area exposures were also estimated in order to compare the effectiveness of exhaust versus dilution. The mean area concentration for GEV was on the order of three times higher than that of GDV (3.23 mg/m^3 and 1.22 mg/m^3, respectively), suggesting that the potential for secondary exposures would be greater under GEV (Figure 2.15).

Area Mixing

As expected based on the relative closeness of the High pDR and Low pDR real-time concentration plots, the space area under the GDV configuration is well mixed (mean vertical mixing ratio of 0.85). Conversely, the mean vertical mixing ratio under the GEV configuration (3.70) indicates a relatively high fume accumulation on the ceiling in the space compared to the floor (Figure 2.16).

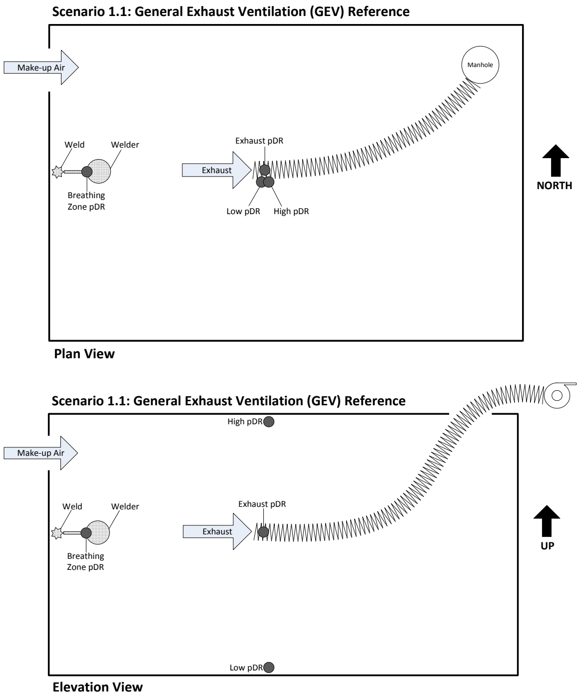


Figure 2.10. Plan and elevation views of Scenario 1.1 (GEV reference), with relative positions of pDRs, ventilation, and weld

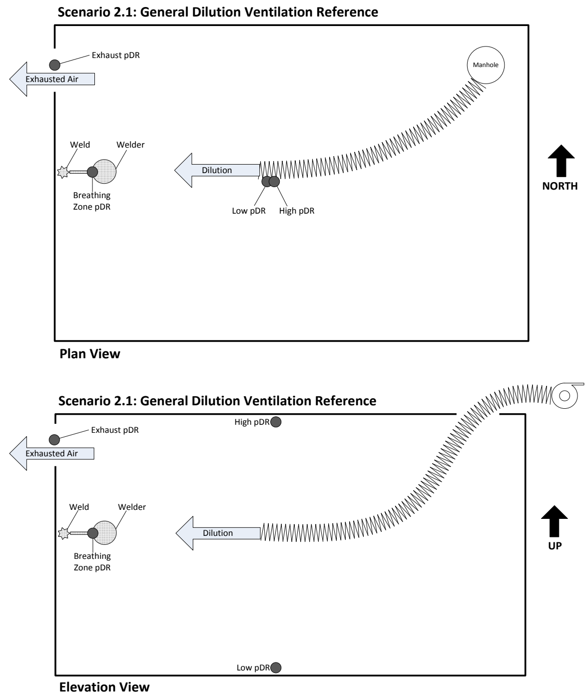


Figure 2.12. Plan and elevation views of Scenario 2.1 (GDV reference), with relative positions of pDRs, ventilation, and weld

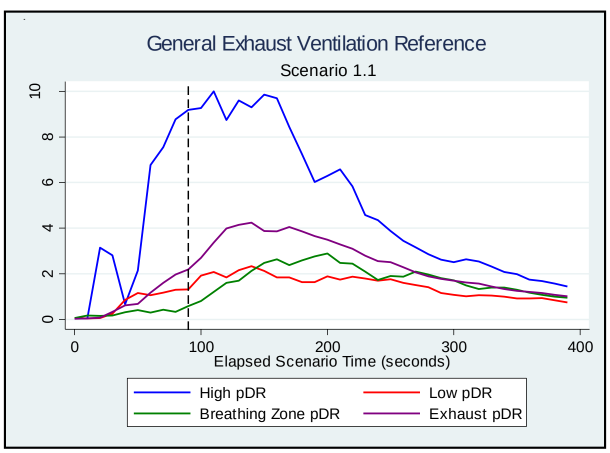


Figure 2.11. Time versus mean concentration for Scenario 1.1 (GEV reference). Vertical dash denotes end of the weld period

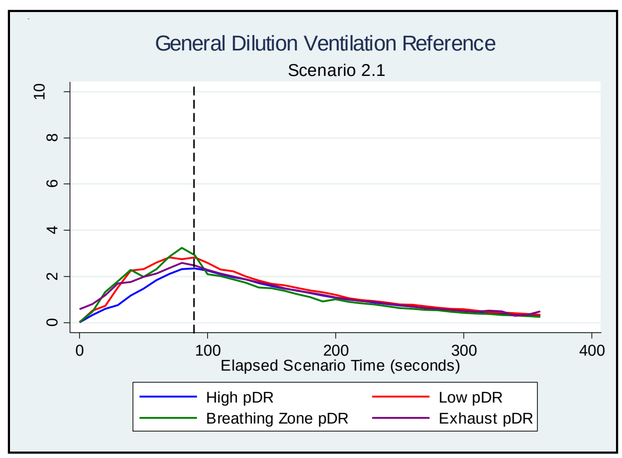


Figure 2.13. Time versus mean concentration for Scenario 2.1 (GDV reference). Vertical dash denotes end of the weld period

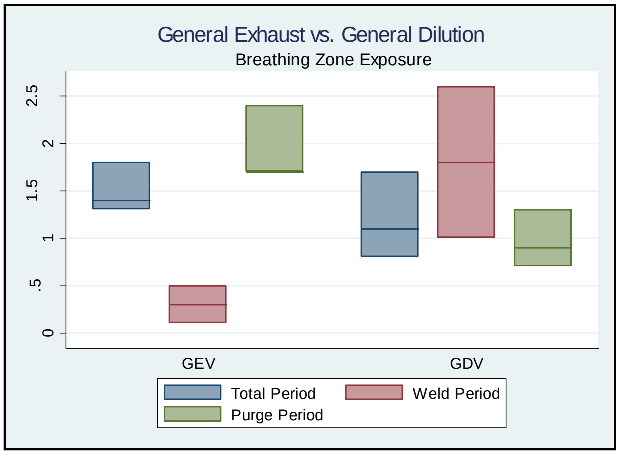


Figure 2.14. Mean welder's breathing zone fume concentration for total, weld, and purge periods for Scenarios 1.1 and 2.1 triplicates

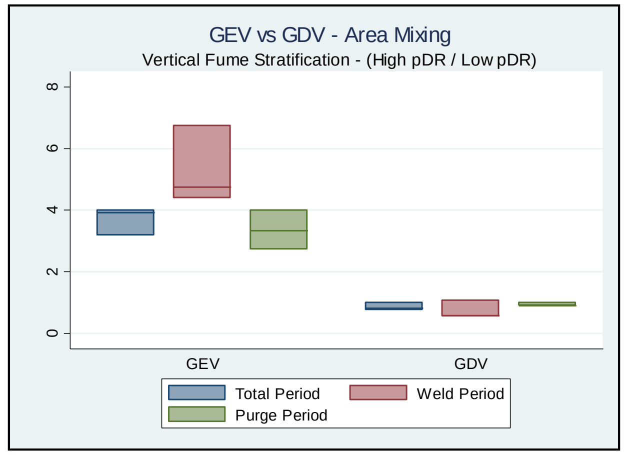


Figure 2.16. Mean vertical mixing ratio for total, weld, and purge periods for Scenarios 1.1 and 2.1 triplicates

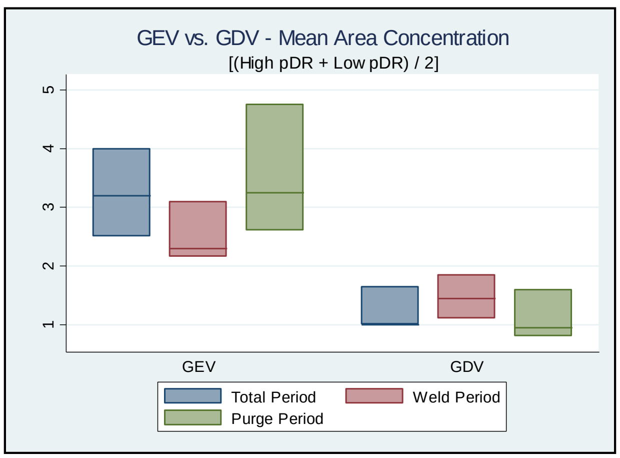


Figure 2.15. Mean area fume concentration for total, weld, and purge periods for Scenarios 1.1 and 2.1 triplicates

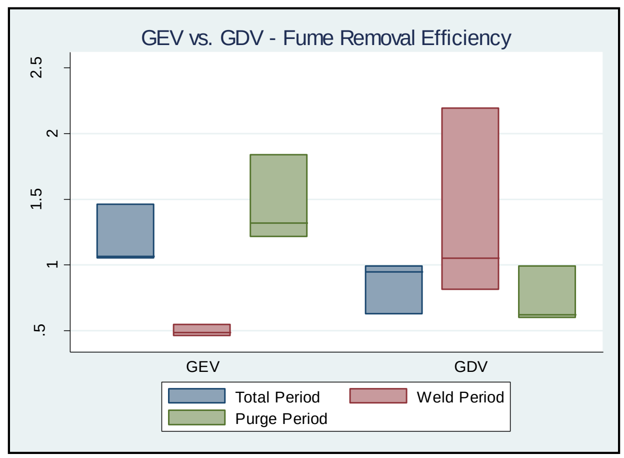


Figure 2.17. Mean fume removal rate for total, weld, and purge periods for Scenarios 1.1 and 2.1 triplicates

Fume Removal

The real-time concentration plots suggest that the relative concentration at the Exhaust pDR mimics that of the Breathing Zone pDR, indicating that the peak of fume removal in the GEV scenario occurs later on in the purge period, compared to the peak in fume removal early on during the weld period for the GDV scenario. To further examine fume removal efficiency, the average fume removal rate over the entire sampling period, which is proportional to the total amount of welding fume removed, was compared (Figure 2.17).

On average, the GEV configuration removed more welding fume than did the GDV configuration. Consistent with the breathing zone concentration results, however, the GDV scenario removed more welding fume early on (during the weld period), compared to the relatively late fume removal effect of GEV.

<u>Position of Ventilation Relative to Weld</u>

The effect of vertical ventilation location relative to the weld was assessed by comparing scenarios where the weld was maintained at a mid-height level and the ventilation ducts were moved to the ceiling and to the floor (1.4 and 1.5 for GEV, respectively; 2.4 and 2.5 for GDV, respectively). Scenario schematics, real-time concentration plots, and metric comparison figures for scenarios considered in this comparison are shown in Figures 2.18-2.21.

Exhaust

The average welder breathing zone exposures differed very little between the High GEV and Low GEV configurations. Additionally, the extent of area mixing within the space was the same when comparing the vertical mixing ratios for the two configurations.

There were slight differences in the efficiency of fume removal between the two configurations. Since the fume concentration is much higher on the ceiling, one could assume that placement of exhaust closer to the top of the ceiling would remove more fume than the same exhaust placed at the bottom of the space. This effect is suggested visually in Figures 2.19 and supported by a higher average concentration in the exhaust duct in the High GEV scenario when compared to the Low GEV scenario (Figure 2.23). Additionally, this effect reduces the fume accumulation at the top of the space resulting in a lower average space concentration available for secondary exposures.

Dilution

The vertical mixing ratio, mean mass removal rate, and average space concentration were similar for High GDV and Low GDV scenarios. This indicates that for dilution ventilation in a simple space, the vertical position of the duct has little effect on the airflows ability to mix the space and push contaminated air out of the space.

The effectiveness of controlling fume concentrations in the welder's breathing zone, however, varied dramatically between the two scenarios. Restricting the comparison to the weld period only results in an average breathing zone concentration of 5.4 mg/m^3 for the High GDV scenario, compared to 1.6 mg/m^3 for the Low GDV configuration (Figure 2.24). This surge in breathing zone exposure is only observed during the weld period, as the mean breathing zone concentrations during the purge period drop to 0.7 mg/m^3 for High and Low GDV. The elevated exposure during welding for Scenario 2.4 can likely be explained by the vertical and directional placement of the duct opening. In the High GDV configuration, air was supplied towards the wall above the welders head, possibly creating an air barrier that would restrict the plumes natural tendency to rise up and out of the welder's breathing zone. Alternatively, in the Low GDV scenario, buoyant nature of the welding fume was likely assisted upwards, resulting in a slight reduction in breathing zone exposure when compared to the GDV reference scenario where air was supplied at mid-height.

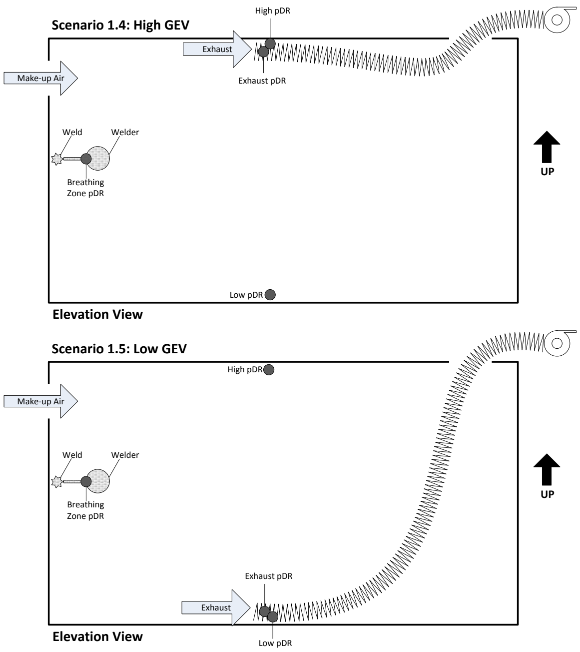


Figure 2.18. Elevation views of Scenarios 1.4 and 1.5 (High GEV and Low GEV)

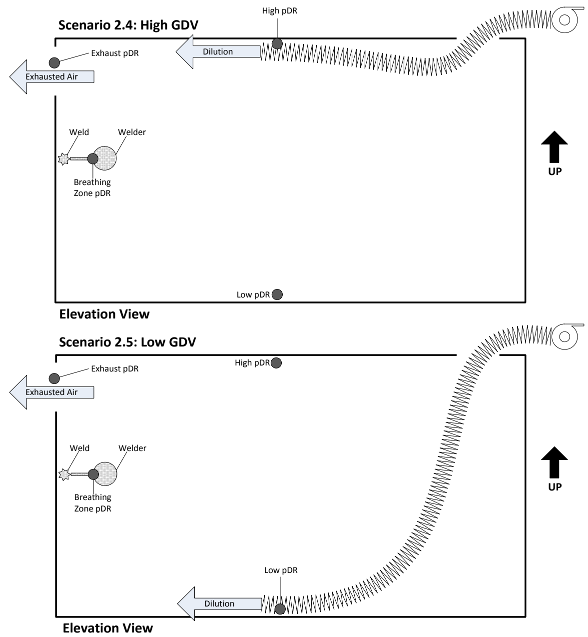


Figure 2.20. Elevation views of Scenarios 2.4 and 2.5 (High GDV and Low GDV)

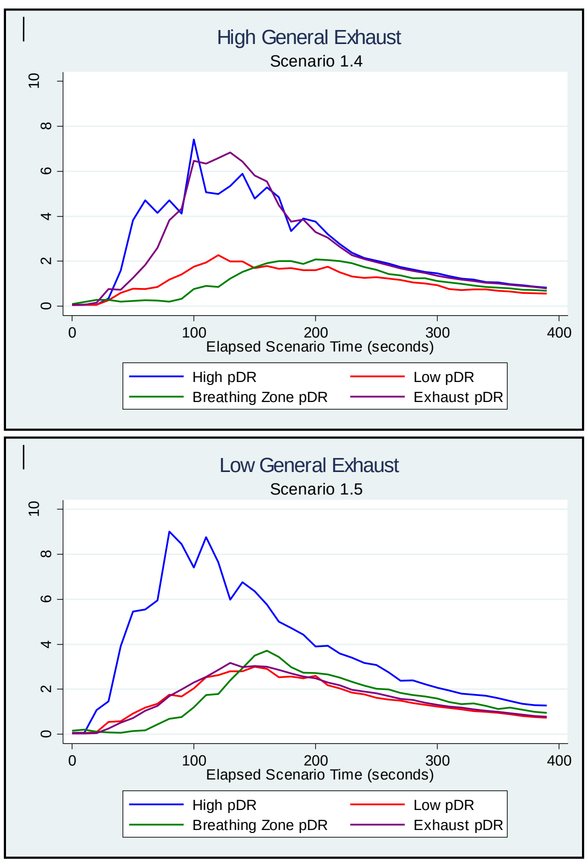


Figure 2.19. Time versus mean concentration for scenarios 1.4 and 1.5; line denotes end of weld period.

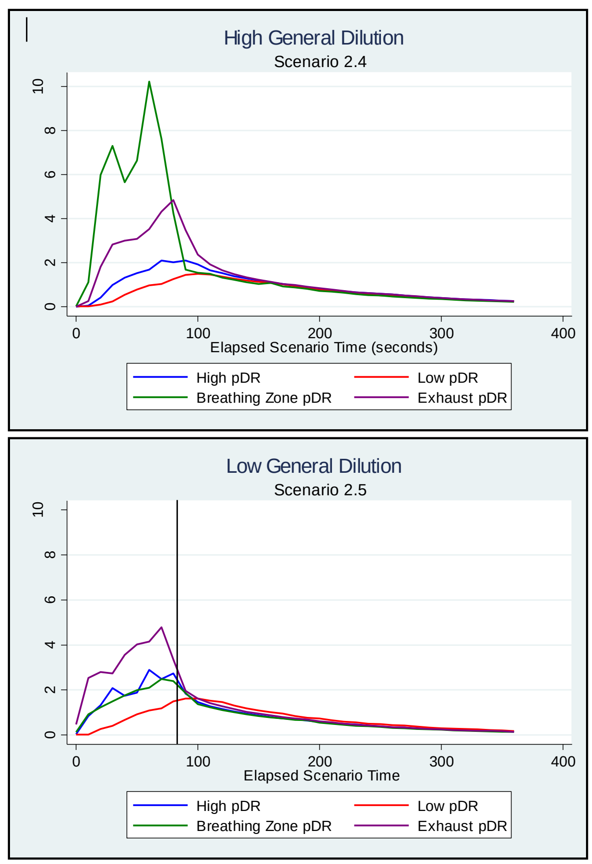


Figure 2,21. Time versus mean concentration for scenarios 2.4 and 2.5; line denotes end of weld period.

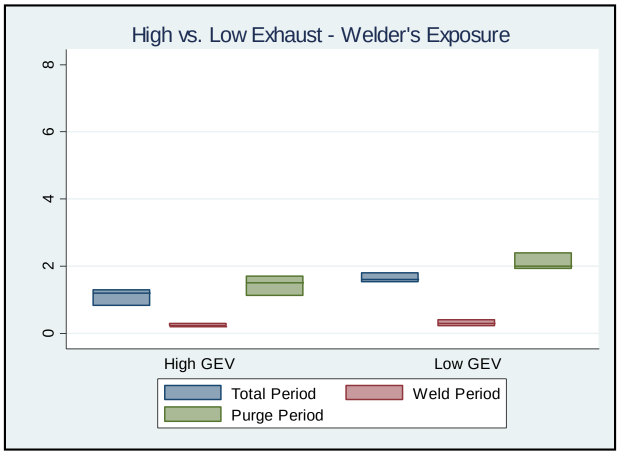


Figure 2.22. Mean breathing zone concentrations for Scenario 1.4 and 1.5 (High and Low GEV) triplicates.

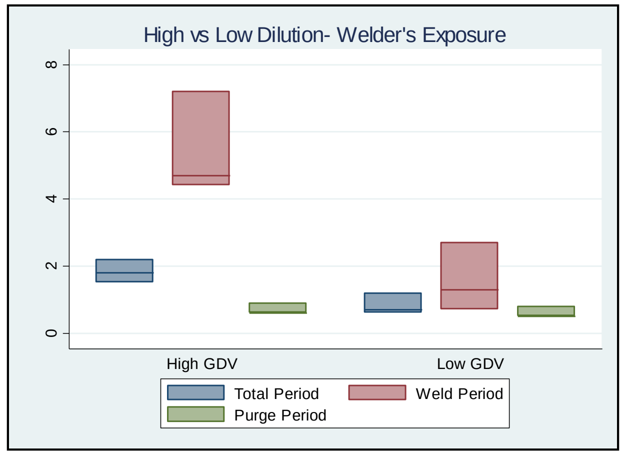


Figure 2.24. Mean breathing zone concentrations for Scenario 2.4 and 2.5 (High and Low GDV) triplicates.

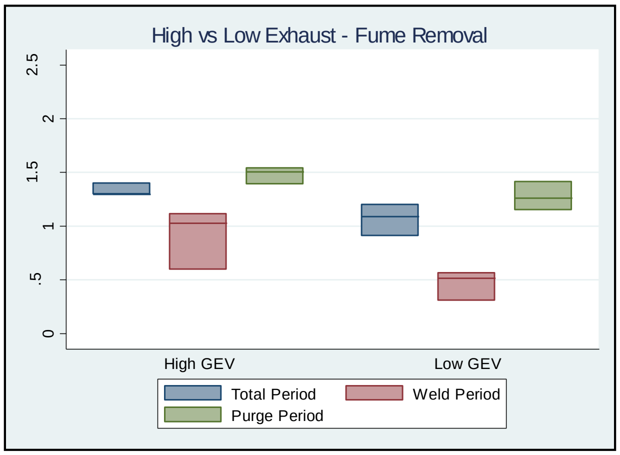


Figure 2.23. Mean fume removal rates for Scenario 1.4 and 1.5 (High and Low GEV) triplicates.

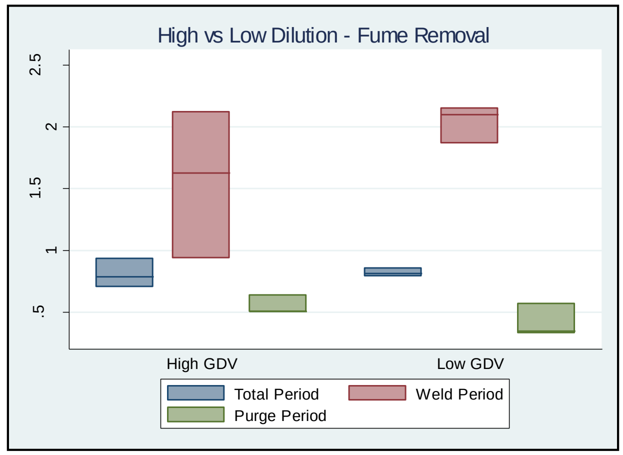


Figure 2.25. Mean fume removal rates for Scenario 2.4 and 2.5 (High and low GDV) triplicates.

Welding in "Dead Space"

For all exhaust scenarios the location of the weld was intermediate to the location of the exhaust and make-up air ports; therefore, the effect of welding in a "dead air space" was only evaluated under general dilution configurations. The Short Circuit Dilution (SCD) Reference scenario was identical to the GDV Reference scenario (2.1), except that the weld was moved to the opposite wall, out of the path of airflow supplied by the ventilation duct (Figure 2.26).

The extent of area mixing (vertical mixing ratio), mean fume removal efficiency, and average area exposure (High pDR/Low pDR) for the SCD Reference scenario were comparable to the GDV Reference scenario.

Personal breathing zone exposure for the welder in the dead space, however, was on the order of double that of GDV Reference scenario (2.5 mg/m^3 versus 1.2 mg/m^3 for Scenarios 3.1 and 2.1, respectively). For the SCD Reference configuration, mean breathing zone concentration peaked during the weld period (5.0 mg/m^3), suggesting that increase in exposure resulting from airflow turbulence is compounded in this situation by the fact that the weld is not performed in the direct path of the supplied air path (Figure 2.27).

Effect of Additional Area Mixing

The effect of area mixing ventilation was assessed by adding a separate area fan (centrifugal blower) that circulated air within the space towards the direction of the wall where the weld was performed (opposite of the airflow supplied by the GDV duct).

Very little differences in effectiveness metrics were observed between the SCD Reference scenario configuration and the SCD + Area Mixing Fan scenario (3.2), with the exception that adding an extra mixing blower in the space resulted in a slightly improved vertical mixing ratio during the weld period when compared to the reference scenario (0.98 and 2.23, respectively).

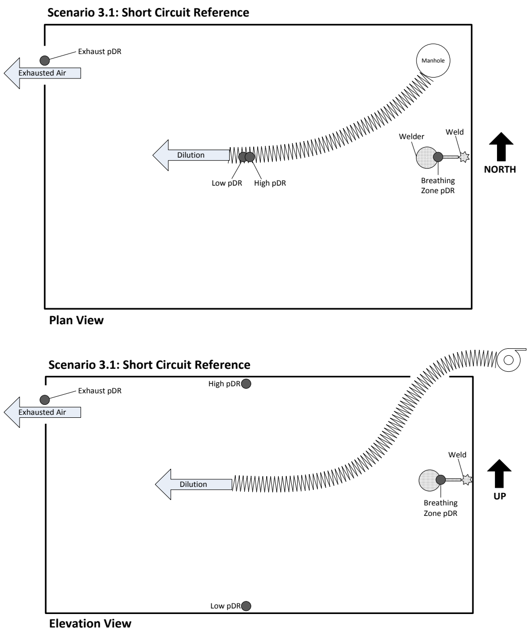


Figure 2.26. Plan and elevation views of Scenarios 3.1 (Short-Circuit Dilution reference)

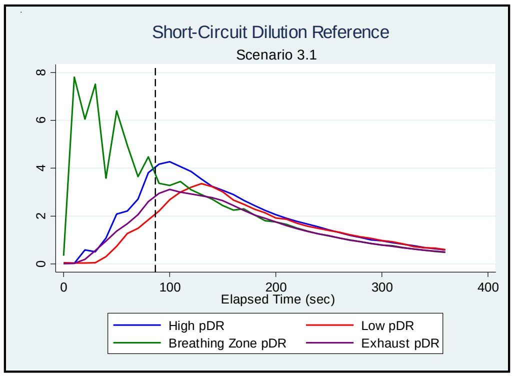


Figure 2.27. Time versus mean concentration for Scenario 3.1 triplicates

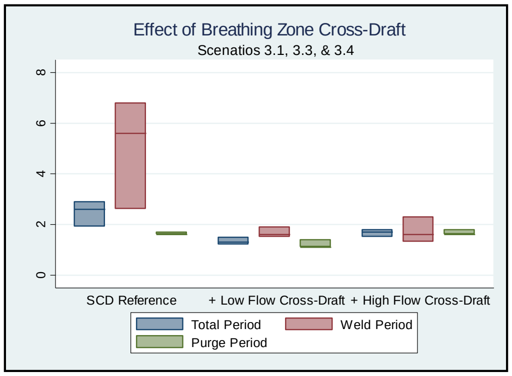


Figure 2.30. Mean weld exposure measurements for Scenario 3.1, 3.3, and 3.4 replicates

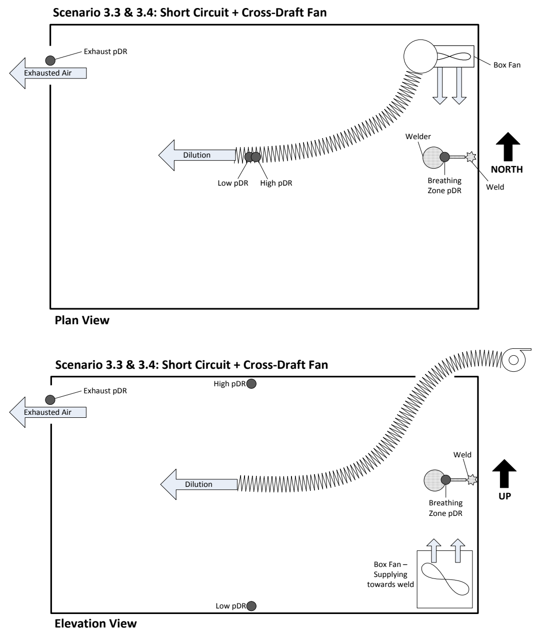


Figure 2.28. Plan and elevation views of scenarios 3.3 and 3.4 [SCD + Cross-Draft (High Flow) and SCD + Cross-Draft (Low Flow)]

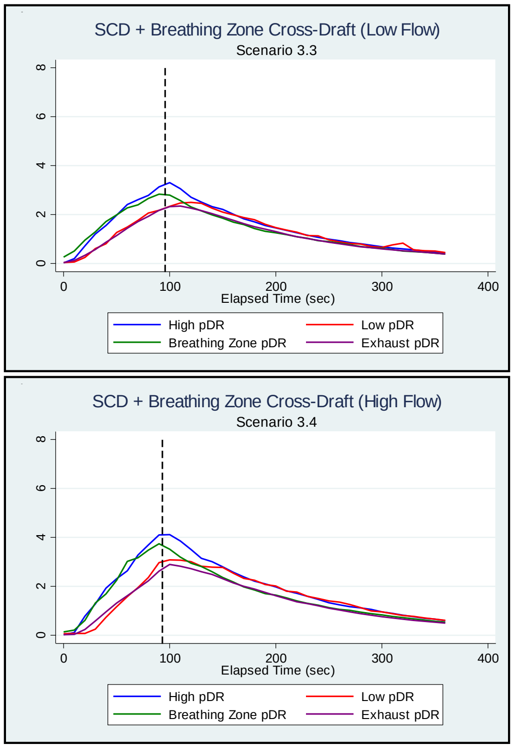


Figure 2.29. Time versus mean concentration for Scenario 3.3 and 3.4 triplicates

Effect of Breathing Zone Cross Draft

The effect of creating an airflow cross draft across the welder's breathing zone was assessed by comparing the SCD Reference scenario to the same configuration with the addition of a box fan supply air across the breathing zone at High Flow (3.3) and Low Flow (3.4) (Figure 2.28). The box fan was set to a constant distance from the weld and the variable speed was adjusted to supply air across the weld at 300 ft/min for the High Flow configuration and 100 ft/min for the Low Flow configuration.

Both High Flow and Low Flow cross draft scenarios reduced the average welder exposure during the weld period when compared to the SCD Reference scenario (from 5.0 mg/m^3 to 1.7 and 1.7 mg/m^3, respectively) (Figure 2.30). No other obvious differences in ventilation effectiveness metrics resulting from the addition of cross draft fans were observed.

Discussion and conclusions

The primary aim of conducting the ventilation experiments was to gain general insight in to how different ventilation techniques compare at controlling the potential for fume exposure in an enclosed space. For each scenario comparison made only one ventilation parameter would be altered; therefore any differences in measured fume concentrations could be explained by the difference in that parameter. However, such a simple experimental design, while allowing for easier interpretation of results, makes it difficult to confidently translate any noticeable trends in to recommendations for the use of ventilation in actual shipyard spaces. Important welding task characteristics such as the shape of the space, the complexity of the interior of the space, the degree of space enclosure, the weld method, and the position of the welder's head relative to the plume were not varied and therefore not evaluated in the experiments. Recognizing the limitations of projecting results from a simple experiment to real work application in dynamic work conditions, some general insights were gained that helped further our understanding of ventilation effectiveness.

When comparing the results from comparisons of GEV and GDV scenarios, for example, some broad patterns were suggested. The mean exposure to the welder differed very little between GDV and GEV configurations. The lower exposures during the GEV weld period suggest that the weld plume rose to the ceiling and had little effect on the breathing zone measurements. The delayed peak in exposure, however, indicates that over time the accumulation of fume in the space combined with poor area mixing can result in increased potential for exposure over time. The increase in the welder's exposure during the weld period for GDV is consistent with the theory that the turbulent effect of supplied air can result in "eddies" in the breathing zone, thereby trapping the plume near the breathing zone and increasing exposure. The mixing effect of GDV, however, resulted in a fairly uniform fume concentration throughout the space, decreasing the pockets of high fume concentration and the potential for secondary exposures in those areas.

The vertical position of the duct was also identified as a key consideration. Exhausting from the top of the space, while having little effect on the welder's exposure during the weld time, removed more fume from the space during the total scenario time, thus reducing the potential for exposures both to the welder and to other workers present in the space over time. For dilution configurations, supplying air above and below the weld both mixed the space well and removed similar amounts of fume. However, there was a dramatic increase in the welder's exposure during the weld time when supplying air above the point of the weld. Recognizing that this increase was probably mostly an artifact of the specific configuration of the experimental design, these results still suggest that general dilution should be supplied to a space at a point below the weld.

Also, the experimental results demonstrate that generating a cross-draft across the welder's breathing zone can significantly reduce exposure during welding. Considering that turbulent air movement could potentially affect weld quality, using a breathing zone cross-draft might still be an effective ventilation technique since reduced welder exposure was observed even at cross-draft velocities as low as 100 ft/min.

Drawing on lessons learned from the ventilation experiments, combined with a synthesis of welding ventilation literature and insights gained from preliminary shipyard welding surveys, the following guidelines and considerations were identified and included in the intervention training (Appendix C):

- Remove fume from the areas of highest concentration, focusing primarily on reducing concentrations in the welder's breathing zone and other areas where other workers might be exposed
- Remove fume from the breathing zone by generating a cross-draft across the breathing zone
- When possible, mix the fume around the space to eliminate areas of elevated concentration
    - Mixing can increase exposure for others in the space, and therefore works best when working alone
- Avoid configurations that result in airflow that does not have an effect on the area of fume generation ("short-circuiting" or collocated of the exhaust and supply)
- When using exhaust ventilation, move the duct as close to the weld as possible
    - LEV is better than REV, which is better than GEV
- Supplied air has a much further "reach" within the space than does exhausted air
- The amount of air moved by a ventilation blower decreases dramatically with the length of the duct and bends in the duct
- The amount of fume in the space and therefore the amount of air required for effective ventilation increases with the number of workers welding in the space
- The accumulation of welding fume occurs much faster in smaller spaces and in spaces with a high degree of enclosure

CHAPTER III: SHIPYARD OBSERVATIONS

Aims

The overall aims of the shipyard ventilation study, of which the work conducted in this thesis has contributed to, were to develop basic ventilation guidelines for shipyard welders, teach those guidelines to welders during a training intervention, and then to assess the adoption of the recommended ventilation practices. The preceding chapter described in part the development of the ventilation guidelines that were used in the intervention training.

Based on the recommended ventilation guidelines, an observational method was developed to measure ventilation-related behavior as defined by the guidelines. Using the observational method, we sought to measure the use of ventilation of shipyard welders at baseline and again after teaching the recommended guidelines to determine if there was a change in ventilation-related behavior post-intervention.

It was concluded that a thorough shipyard observation survey should be conducted to evaluate the use of the observational method and characterize baseline use of the recommended ventilation guidelines at the study shipyard.

The specific aims of the shipyard observations were as follows:

1. Evaluate the observational method by determining ventilation-related behavior as defined by the recommended ventilation guidelines
    - Assess the inter-observer reliability of the observation tool
    - Compare exposure to the observed use of ventilation and perceived effectiveness of ventilation

2. Characterize baseline shipyard welder work practices and use of ventilation
    - Identify common ventilation challenges and areas for improvement
    - Further our understanding of shipyard welding to inform the approach to assessing the effectiveness of the intervention training

Methods

Shipyard surveys

Shipyard

Shipyard observations were completed at Vigor Shipyard in Seattle, WA (formerly Todd Pacific Shipyard) from January 1, 2012 to May 9, 2012. Located on 27 acres on Harbor Island, Vigor Seattle has three dry-docks, six piers, multiple fabrication shops, and more than 900 employees, making it the largest shipyard in the Pacific Northwest. Vigor specializes in the construction, repair, and modernization of a variety of marine vessels, including passenger ferries, military vessels, barges, and fishing vessels.

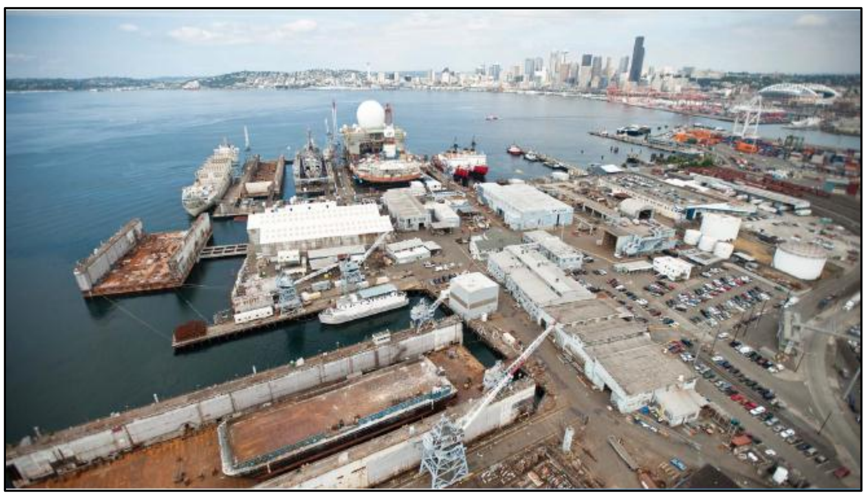


Figure 3.1. Vigor Shipyard on Harbor Island, overlooking Elliot Bay and Downtown Seattle, WA

Welding observations

In coordination with Vigor health and safety personnel and welding supervisors, all relevant enclosed and confined space welding operations were identified on a day-by-day basis. Sampling was performed every week-day during the study period, except when welding activity levels and the probability of performing observations were low. On average, about three sampling days were performed each week. At the beginning of the study, the identification of appropriate welding tasks was dependent on our shipyard contact's familiarity with the day's welding operations. After a few weeks, however, key relationships were established with welders, project managers, and welding supervisors, allowing for research observers to survey the shipyard for enclosed and confined space welding without a shipyard escort.

Observations were attempted for all welding and hot-work tasks that were performed in enclosed or confined spaces. When relevant work was identified, researchers would introduce themselves to the worker, explain the study and purpose for the observation, and receive verbal consent before initiating the observation. When possible, approval was gained from area supervisors prior to approaching the worker. The observational assessment method was approved by the University of Washington Institutional Review Board prior to data collection.

Upon receiving verbal consent, the worker was equipped with a real-time particulate monitor and asked to continue work as usual. Once the worker resumed welding or hot-work, the observation "start" time was recorded and the task was observed continuously for approximately 10 minutes. The protocol for completing each welding observation was as follows:

1. Identify relevant enclosed/confined space welding task
2. Receive verbal consent from the observed worker
3. Start personal particulate sampling monitor, record sample number, and attach in the worker's breathing zone
4. Wait for worker to resume hot-work, begin observation, record the "start" time
5. Observe the task for 10 minutes
6. Characterize the work, space, and use of ventilation using the observation tool
7. End the observation, record the "stop" time, and retrieve the particulate sampling monitor from the worker
8. Continue surveying the shipyard for other relevant welding tasks

<u>Observation tool</u>

Researchers performed the baseline shipyard assessments using an observation tool based on the recommended ventilation guidelines (Appendix D). Blank field hard-copies of the observation form were completed by hand for each observation and entered in to an electronic dataset at the end of each sampling day. Observation form data collected can be summarized by four categories: work characteristics, space characteristics, use of ventilation, and perceived ventilation effectiveness ratings. Following is a summary of each of the questions on the observation form along with possible answers and reporting criteria:

Work characteristics:

Type(s) of work performed by the observed worker:

- Welding/hot-cutting, grinding, fitting/tacking, chipping/scaling, pre-work, fire-watch, or other

Weld method used:

- Stick, TIG, MIG, FCAW, carbon arc cutting ("scarfing"), oxy-acetylene welding/cutting, other

How many minutes out of the observation time were spent welding

- For example, 6 minutes welding out of 11 total observation minutes

Proximity of the worker's head to the plume

- In plume, near plume, away from plume
    - A subjective assessment of the location of the welder's head relative to visible fume.
        - In plume: welder's breathing zone in the path of the most concentrated portion of the generated welding fume
        - Near plume: welder's breathing zone still in welding fume, but in an area of reduced visible concentration
        - Away from plume: welder's breathing zone completely out of the visible fume

Total number of other workers present in the space (not including the observed worker)

Total number of other welders in the space (not including the observed worker)

Type of respirator used

- No respirator, half-face air-purifying, full-face air-purifying, powered air-purifying, supplied air, disposable

Apparent fit of the respirator

- Good, poor, unsure
    - Good: worker was clean-shaven
    - Poor: worker was not clean-shaven

Space characteristics:

Shape of the work space

- Simple or complex
    - Simple: spaces with simple box-like geometries, not more than five walls, free of major interior obstructions
    - Complex: spaces with more than five walls and/or major interior obstructions

Type of work

- New construction or repair

Type of space

- Partially enclosed space, enclosed space, confined space
    - Partially enclosed: has the potential for restricted air movement and fume accumulation, but has at least one large opening
    - Enclosed: Closed on all sides, but does not fit the definition of a permitted confined space
    - Confined: limited access of access and egress, not designed for continuous human occupancy

Space dimensions (as measured with a laser tape measure)

- Approximate average height, width, and length of the space

Use of ventilation:

Exhaust ventilation:

How many blowers are exhausting the space?

Exhaust duct ventilation rate information for each exhaust duct

- Linear air velocity (ft/min): measured by performing a traverse at the duct opening with a rotating vane anemometer (TSI VelociCalc® 9565 Air Velocity Meter)
- Duct diameter (in.)

Proximity of exhaust opening to the point of fume generation (completed for each exhaust duct present)

- Local exhaust, regional exhaust, general exhaust
    - Local: within two duct-diameters of the weld
    - Regional: within five feet of the weld
    - General: further than five feet from the weld

Dilution ventilation:

How many blowers are supplying air to the space?

Supply duct ventilation rate information for each supply duct

- Linear air velocity (ft/min): measured by performing a traverse at the duct opening with a rotating vane anemometer
- Duct diameter (in.)

Other ventilation characteristics:

How is the air within the space being mixed?

- Not mixed, supply blower, mixing fan, natural ventilation

Is there cross-draft airflow across the worker's breathing zone?

- Yes or no

How is the cross-draft generated?

- Natural ventilation, supply blower, mixing fan, no cross-draft

Is the work performed in airflow dead-space?

- Yes or no
    - Dead-space: subjective assessment of whether weld is performed out of the effective "reach" of the ventilation airflow
    - Not in dead-space: weld is performed within the path of ventilation airflow

Are the air supply and exhaust points collocated?

- Yes or no

Is the supplied air (dilution ventilation configurations) or make-up air (exhaust ventilation configurations) free of air contaminants?

- Yes or no
    - A subjective assessment to the contamination in air entering the space, usually based on activity in adjacent areas

Is the ventilation increasing exposure for other workers in the space?

- Yes, no, unsure
    - Yes: the ventilation configuration is increasing the potential for exposure in others in space, compared to exposure that would be expected in the absence of that configuration

Perceived ventilation effectiveness:

Mixing:

- Given the work and space characteristics, is the mixing or lack of mixing appropriate?
    - Appropriate or inappropriate
        - Appropriate

        - Mixed: space shape is simple, does not increase exposure to other workers, spaces open to outdoors
        - Unmixed: space is complex, other workers present in the space, space is in the interior of a vessel
    - Inappropriate
        - Mixed: space is complex, mixing increasing exposure to other workers, space is on the interior of a vessel
        - Unmixed: space is simple, no other workers present in the space, space open to outdoors

<u>Cross-draft:</u>

- If there is a cross-draft across the worker's breathing zone, how effectively is it reducing the potential for exposure?
    - Effective, partially effective

<u>Individual ventilation component score (completed for each exhaust and supply duct):</u>

- How effective is this ventilation duct at reducing the potential for welding fume exposure?
    - High, medium, low, zero/not present

<u>Aggregate ventilation score:</u>

- Overall, how effective is the ventilation in the space at reducing the potential for welding fume exposure?
    - High, medium, low, no ventilation

Exposure estimation

Welding fume exposure was estimated by measuring total particulate concentration in the breathing zone of the observed welder with the same MIE Personal DataRAM™ particulate monitors (pDRs) described in Chapter II. Monitors were set to sample in active mode at 10-second- average logging intervals. Air was drawn through the pDR measurement chamber using SKC AirCheck XR5000 personal air sampling pumps which were calibrated to 2.0 liters per minute before each sampling day with a primary air flow meter. To limit the loss of welding fume due to electrostatic forces, air was drawn into the pDR using a 3.5 foot length of conductive silicone tubing, the terminal "up-stream" end of which was attached to the lapel of the observed worker. The calibration of each pDR was checked before each sampling day by performing the internal span check ("zeroing") procedure specified in the instrument user instruction manual. Figure 3.2 shows the sampling train used for all shipyard observation exposure measurements.

Internal pDR clocks were synchronized to a reference time on a designated study computer at the beginning of each sampling day. Field watches were also matched to that time so that continuous pDR concentration data could be truncated to the recorded observation interval.

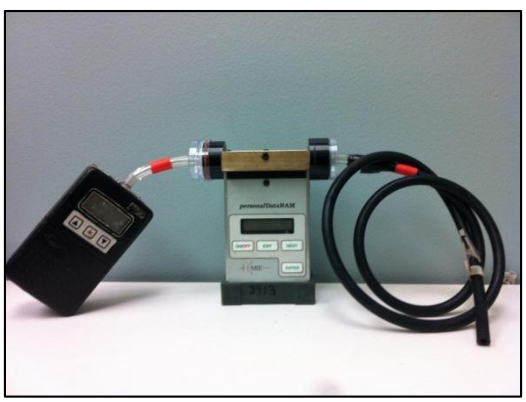


Figure 3.2. Particulate sampling train used for total particulate exposure measurements for shipyard observations. From down-stream to upstream: personal air sampling pump, pDR particulate monitor, 3.5 feet of conductive tubing, open sampling end attached in breathing zone of observed worker.

Analysis

Hard-copy observation form data were manually entered in a master Excel database at the end of each sampling day. For each observation, volumetric flow rates for each ventilation duct and total space ventilation rates were computed and entered as separate variables for each observation. Continuous breathing zone pDR data was uploaded and entered in to observation-specific Excel spreadsheets, then matched and truncated to the nearest 10-second intervals corresponding to the recorded observation start and end times. The mean concentration over the observed time was calculated and entered in the master Excel database as the estimated exposure concentration for each observation.

Three datasets were compiled using the observation form data. First, data for all shipyard observations (*n=36*) were used to summarize baseline space and work characteristics, use of ventilation, and perceived effectiveness. For observations that where completed by two side-by-side observers, only the observation form data completed by the author was included in the analysis. Summary statistics were used to compare the frequencies of work, space, and use of ventilation variables across key comparison categories such as the weld method, degree of enclosure and space volume. The second dataset consisted of only observations that had matching breathing zone exposure measurements (*n=33, 29*). Mean exposure measurements for three welding method categories were compared across space and ventilation-related variables to explore the relationship between exposure the use of ventilation. Additionally, a multi-regression analysis was performed to evaluate if the current use of recommended ventilation practices was related to total particulate exposure. Lastly, a third dataset consisting of only observations completed by side-by-side observers (*n=11*) was used to evaluate the inter-observer reliability of the observational method. All three databases were uploaded and analyzed using Stata 12(StatCorp, College Station, TX).

Ventilation rate

For each observation the total ventilation duct volumetric flow (Q_t) rate was calculated by summing the volumetric flow rate for each ventilation duct supplying or exhausting the space following the equation:

$$Q_i = v \times A \text{, where}$$

- Q_i= the volumetric flow rate for each individual ventilation duct in ft^3/min
- v = the linear air velocity measured at the duct opening in ft/min
- A = the area of the duct opening in ft^2

The space ventilation rate was estimated by calculating the number of times the ventilation replaced the volume of air within the space every minute ("air changes per minute" or ACM). For comparison, the space ventilation rate for the minimum amount of air required by OSHA (2,000 ft^3/min) for one welder in a 10,000 ft^3 space is 0.2 ACM (OSHA, 1993). For each observation ACM was calculated using the equation:

$$ACM = \frac{Q_t}{V} \text{, where:}$$

- *ACM* = the space ventilation rate in air changes per minute
- Q_t = the total volumetric flow rate for all ventilation ducts in in ft^3/min
- V = the volume of the space in ft^3

Observations with no mechanical ventilation were assigned a ventilation rate of zero ACM, assuming that natural ventilation airflow would have a negligible effect due to the enclosed nature of the types of spaces surveyed.

Results

Inter-observer reliability

A total of eleven observations were performed in duplicate by side-by-side assessments of the same welding task by two different research observers. To assess the inter-observer reliability of the observational tool, percent agreement between observers was calculated for both objectively reported (space and work characteristics) and subjectively reported (ventilation effectiveness ratings) observation form questions (Table 3.1).

Table 3.1. Inter-observer agreement for side-by-side shipyard observations

Observation form question	Percent agreement (%)
Space shape	100
Job type	100
Degree of enclosure	100
Number of workers	91
Weld method	100
Number of ventilation ducts	100
Exhaust duct proximity	100
Nearest vent. duct effectiveness	91
Welding in deadspace?	73
Proximity of head to plume	82
Increased other worker's exposure?	83
Room mixing effectiveness	64
Overall ventilation effectiveness	91

Overall, inter-observer agreement for the observation tool was good, considering that there were only 11 side-by-side measurements. Agreement between research observers was perfect for questions that characterized the observed space (shape of the space and degree of enclosure), the welding method used, the job type, the number of ventilation ducts present in the space, and the proximity of exhaust ventilation ducts relative to the weld. Good agreement is suggested for the reporting the number of workers in the space, the proximity of the welder’s head to the plume, the rated effectiveness of the ventilation duct closest to the weld, the overall ventilation effectiveness rating, and assessing if the ventilation was increasing exposure for other workers in the space.

Agreement was not as good for determining whether or not the welder was in ventilation dead space. When mechanical ventilation was present, determining whether a location is in airflow dead space is not always clear-cut, since there is never an obvious cut off point at which the airflow ceases to be effective.

Lastly, agreement was poorest for reporting the appropriateness of the use of mixing within the space. As outlined earlier, there are multiple factors that were considering in assigning the mixing rating, such as the shape and size of the space, the presence of interior obstructions, and the presence of other workers. The application of these general reporting guidelines to specific work spaces was often challenging and subject to the observer's opinion for how mixing should be used.

<u>Factors contributing to overall effectiveness rating</u>

To examine how the overall effectiveness score was used during the shipyard observations, individual space, work, and ventilation observation form questions were compared the overall rating. For each applicable observation question, the data were ranked in ascending order of presumed effectiveness to match the ordinal "zero, low, medium, high" overall score ranking. For example, when comparing the proximity of the welder's head to the plume to the overall score, head proximity data were ranked from least to most presumed potential for fume exposure: "in plume, near plume, away from plume." For each comparison, a Fisher's exact test was performed to examine the significance of the association. Table 3.2 shows the significance levels for each overall score versus individual observation form question comparison.

Table 3.2. Fisher's exact p-values comparing overall score with other ventilation related observation variables.

Overall ventilation score compared with:	**All observations** *(n=36)*	**Excluding obs. with no ventilation** *(n=21)*
Weld method *(flux core, oxy-gas, stick, MIG)*	0.03	0.07
Space type *(complex, simple)*	0.09	0.43
Space shape *(confined, enclosed, partially enclosed)*	0.94	1.00
Proximity of head to plume *(in plume, near plume, away from plume)*	0.18	0.07
Type of ventilation *(no ventilation, dilution, exhaust) & (dilution, exhaust)*	< 0.01	0.66
Proximity of exhaust duct (if exhaust ventilation) *(general, regional, local)*	NA	0.04*
Use of space mixing *(unmixed, mixed)*	0.13	0.58
Space mixing score *(inappropriate, appropriate)*	0.48	0.52
Weld performed in dead space? *(in dead space, not in dead space)*	<0.01	0.01
Breathing zone cross-draft *(no cross-draft, partially effective crossdraft)*	0.37	1.00
Exhaust and supply collocated? *(collocated, not collocated)*	0.43	0.43

**n=19*

Researcher characterization of the weld method, ventilation type (when "no ventilation" was included), proximity of the nearest ventilation duct, and welding in dead space were all significantly related to the rating of the overall ventilation rating.

The distributions of overall ratings differed for observations when categorized by the weld method used. Stick, MIG and oxy-gas observations received move effective aggregate rating scores, about 60% of observations rating as "medium" or "high for both method categories, when compared with FCAW observations, which were rated as "medium" only two of the 17 times it was observed and never rated as highly effective. Over half of the FCAW welding tasks were performed in spaces lacking ventilation, and were received an overall score of zero, or "not present.” One initial impression was that this association could be the result of FCAW welders simply not using ventilation as often stick, MIG, and oxy-gas welders. To address this issue, the same comparison was made excluding all observations that lacked mechanical ventilation. The result showed that, when ventilation was used, the weld method used remained significantly associated with the overall ventilation rating. No obvious differences in the space characteristics or ventilation set-up and weld method were identified, suggesting that the effect of weld method on the overall score was independent. One interpretation of this association is that the differences in visible fume generation between the weld methods influence the overall perception of the configuration. For example, assuming identical ventilation use, MIG welding task would likely be rated as more effective at controlling the potential for exposure than a FCAW welding task.

The classification of exhaust duct proximity was also significantly associated with the overall ventilation score. Looking just at observations that used exhaust ventilation, the proximity of the nearest exhaust intake to the weld is logically associated with the perceived overall effectiveness. All welding tasks that used LEV were rated as highly effective overall, tasks that used REV received scores of either “high” or “medium”, and observations that had GEV received scores of either” medium” or “low”, with no GEV configurations that were perceived as highly effective overall for the control of weld fume.

Lastly, the variable characterizing whether the weld was performed in dead space or not was also associated with the overall ventilation score. Also, comparing the location of the weld in relation to the ventilation air-flow (either in dead space or not in dead space) with the overall score for all observations showed a significant relationship. Observations were no ventilation present, however, were always assigned an overall score of zero (“not present”) and also always characterized as being in air-flow dead space. Restricting the comparison to only observations with mechanical ventilation demonstrates the same relationship between location of the weld relative to the ventilation and the overall perceived effectiveness. Three of the nine observations where the welder was in the area of ventilation air-flow generated were rated as highly effective overall. Conversely, for ventilated spaces where the welder was out of the path of air movement 75% received an overall ventilation effectiveness rating of “low”, and none were rated as highly effective.

Baseline characterization of work and use of ventilation

A total of 36 unique welding tasks were observed over the course of the survey period. Observed space characteristics, work characterizes, use of ventilation, and perceived ventilation effectiveness ratings were summarized based on relative frequencies observed for all observations and stratified by the weld method and the degree of enclosure of the work space (Tables 3.3, 3.4, and 3.6).

Space characteristics (Table 3.3)

The majority of observations (78%) were made on repair welding activity; eight observations (22%). Welders were most commonly observed performing work in simple enclosed spaces. Twenty-eight of the total 36 spaces were box-like in geometry (e.g. fuel tanks, inside of ship hulls) and free of major interior obstructions, while the remaining 8 observations were in spaces with a more complex geometry and/or objects in the space (e.g. engine rooms, bulkhead/traverse-fragmented double-bottom hulls).

Partially enclosed and confined spaces were more commonly characterized as complex (50% and 37%, respectively) than enclosed spaces, which were classified as simple spaces 80% of the time. Additionally, the degree of space enclosure seemed to be slightly greater for new construction welding tasks, since all observed new construction welding was performed in either enclosed or confined spaces.

The size of the work spaces varied considerably, from a 40 ft^3 segment on the interior of a double-bottom hull to a 33,600 ft^3 empty ship hold. Not surprisingly, the volume of the space decreased with the degree of enclosure. On average partially enclosed spaces were about 50% larger than enclosed spaces, and enclosed spaces were approximately four times larger than confined spaces; likely due to that fact that new construction welding was performed on spaces that would often not normally be accessed after construction was completed.

Table 3.3. Work and space characteristics for all shipyard observations ($n = 36$)

		All obs. (n/%)	Weld method (n/%)						Degree of enclosure (n /%)			Space Volume (ft^3)	
			SMAW	**TIG**	**MIG**	**FCAW**	**Scarfing**	**Oxy-gas**	**Partially enclosed**	**Enclosed**	**Confined**	**Mean**	**SD**
	***n* =**	36	4	3	4	19	1	5	4	24	8	36	
Weld method	**SMAW**	4 (11)							2 (50)	1 (4)	1 (12.5)	5859	7784
	TIG	3 (8)							.	3 (12.5)	.	5897	2952
	MIG	4 (11)							.	4 (17)	.	590	158
	FCAW	19 (53)							1 (25)	15 (62.5)	3 (37.5)	5138	9991
	Scarfing	1 (1)							.	1 (4)	.	33633	.
	Oxy-gas	5 (14)							1(25)	.	4 (50)	2856	3361
Degree of Enclosure	**Partrially enclosed**	4 (11)	2 (50)	.	.	1 (5)	.	1 (20)				8538	5705
	Enclosed	24 (67)	1 (25)	3 (100)	4 (100)	15 (79)	1 (100)	.				5955	10759
	Confined	8 (22)	1 (25)	.	.	3 (16)	.	4 (80)				1493	2330
Space shape	**Simple**	28 (78)	3 (75)	.	4 (100)	17 (89)	1 (100)	3 (60)	2 (50)	21 (88)	5 (63)	5669	10317
	Complex	8 (22)	1 (25)	3 (100)	.	2 (11)	.	2 (40)	2 (50)	3 (12)	3 (37)	3788	3170
Type of work	**New Construction**	8 (22)	.	.	.	6 (32)	.	2 (40)	.	5 (21)	2 (38)	208	113
	Repair	28 (78)	4 (100)	3 (100)	4 (100)	13 (68)	1 (100)	3 (60)	4 (100)	19 (79)	5 (62)	6691	10008
Proximity of head to plume	**In plume**	7 (20)	.	.	.	7 (37)	.	.	.	5 (21)	2 (25)	6371	12171
	Near plume	17 (47)	2 (50)	1 (33)	2 (50	10 (53)	1 (100)	1 (20)	2 (50)	12 (50)	3 (37.5)	6279	10854
	Away from plume	12 (33)	2 (50)	2 (67)	2 (50)	2 (10)	.	4 (80)	2 (50)	7 (29)	3 (37.7)	3141	3195
Respirator Used	**No**	12 (33)	1 (25)	1 (33)	1 (25)	6 (32)	.	3 (60)	2 (50	8 (33)	2 (25)	4258	8993
	Yes	24 (67)	3 (75)	2 (67)	3 (75)	13 (68)	1 (100)	2 (40)	2 (50)	16 (67)	6 (75)	5747	9461
Total # of other workers in space	**0**	11 (31)	.	.	2 (50)	8 (42)	.	1 (20)	.	9 (37)	2 (25)	3361	9530
	1	18 (50)	4 (100)	.	2 (50)	9 (47)	1 (100)	2 (40	3 (75)	10 (42)	5 (62.5)	4886	8312
	>1	7 (19)	.	3 (100)	.	2 (11)	.	2 (40)	1 (35)	5 (21)	1 (12.5)	9158	11065

Welding

Over half of all the observed welders were using the wire-feed FCAW method for mild steel (FCAW). The other weld methods observed, in order of decreasing frequency, were oxy-gas torch cutting/welding, stick, MIG, TIG, and carbon arc cutting (scarfing). All weld methods were observed in use during repair tasks, while only FCAW and oxy-gas methods were used during new construction observations.

The proximity of the welders head to the welding plume was characterized as either in or near the plume for two-thirds of all observations. For SMAW, MIG, FCAW, and scarfing, the welders head was in or near the plume for at least half of all observations. For the TIG and oxy-gas methods, however, the welder's head was away from the plume for the majority of observed tasks using those methods (67% and 80%, respectively). Two-thirds of observed welders used respiratory protection, which were almost always half-face air-purifying respirators. No major differences in use of respiratory protection between weld method were observed.

Other workers

The two most common welding scenarios encountered were either a welder working alone or a welder working with a fire-watch in the space; 80% of all observations fell in to one of those two categories. Six observations had two to four workers other than the observed welder in the space, while one observation recorded a total of nine additional workers. Of the scenarios that had workers other than the subject and a fire-watch in the space, only three had other welders. There were never more than two welders in an observed space at the same time.

No obvious trend between the degree of space enclosure and the number of workers in the space was observed. However, the number of workers present in the space decreased with the with the space volume. On average, the size of the spaces with one or two total workers was half that of spaces with more than two workers (mean space volume of 4300 ft^3 and 9150 ft^3, respectively).

Use of ventilation (Table 3.4)

Forty-two percent of welding tasks observed were performed in the absence of mechanical ventilation. Of the 21 observations that did have operating ventilation within the space, over 90% used exhaust ventilation, while just two observed welding scenarios used dilution ventilation. Most observed exhaust ventilation configurations had only one exhaust duct present; only three configurations had two ducts exhausting air from the space. The three observations with two exhaust ducts were in relatively large spaces compared to spaces that were exhausted by only one duct; the average space volume for scenarios with two exhaust ducts was 15,500 ft^3, compared to an average volume of 5,300 ft^3 in spaces with a single exhaust duct.

GEV was the most common ventilation strategy employed within exhaust ventilation observations, and the second most common configuration for all researcher observations after no ventilation, present in one-third of all 36 unique welding tasks characterized. The more proximal exhaust configurations, LEV and REV, were used less often that GEV.

Observations of the FCAW weld method (the most commonly observed method and recognized among shipyard welders as having one of the highest fume generation rates) recorded no ventilation used in over half of the welding activities. Only one FCAW observation had REV, while the remaining seven exhausted FCAW configurations used GEV. Another unexpected result was the high rate of use of LEV (50%) and REV (25%) with the MIG weld method, which produces relatively little visible fume compared to the other methods.

Also, all three TIG welding tasks were performed in the absence of ventilation. Despite the fact that TIG produces only small amounts of visible fume, one might expect TIG welders to use ventilation more often and more effectively to reduce the potential to carcinogenic components of stainless steel fume like nickel and hexavalent chromium.

Airflow across the welders breathing zone was observed only three times during the survey period. All cross-drafts were generated by natural ventilation breezes and seemed to occur mostly as the result of coincidental placement of the weld and position of the welder's body.

Table 3.4. Use of ventilation for all shipyard observations ($n = 36$)

		n	All obs. (n/%)	Weld method (n/%)						Degree of enclosure (n/%)			Space Volume (ft^3)	
				SMAW	**TIG**	**MIG**	**FCAW**	**Scarfing**	**Oxy-gas**	**Partially enclosed**	**Enclosed**	**Confined**	**Mean**	**SD**
Type of vetilation	**None**	36	15 (42)	1 (25)	3 (100)	.	9 (47)	.	2 (40)	2 (50)	9 (38)	4 (50)	2473	2770
	Exhaust		19 (53)	3 (75)	.	4 (100)	8 (42)	1 (100)	3 (60)	2 (50)	13 (54)	4 (50)	7682	12033
	Dilution		2 (5)	.	.	.	2 (11)	.	.	.	2 (8)	.	2982	3773
Proximity of nearest exhaust duct	**Local**	19	3 (16)	1 (33)	.	2 (50)	.	.	.	.	3 (23)	.	588	378
	Regional		4 (21)	.	.	1 (25)	1 (13)	1 (100)	1 (33)	.	3 (23)	1 (25)	10573	15646
	General		12 (63)	3 (75)	.	1 (25)	7 (87)	.	2 (67)	2 (100)	7 (54)	3 (75)	8492	12355
Breathing zone cross-draft?	**No**	36	33 (92)	3 (75)	3 (100)	4 (100)	18 (95)	1 (100)	4 (80)	2 (50)	23 (96)	8 (100)	5003	9362
	Yes		3 (8)	1 (25)	.	.	1 (5)	.	1 (20)	2 (50)	1 (4)	.	7973	8287
Weld performed in deadspace?	**Yes**	36	25 (69)	2 (50)	3 (100)	.	16 (84)	1 (100)	3 (60)	2 (50)	16 (67)	7 (87.5)	4583	8831
	No		11 (31)	2 (50)	.	4 (100)	3 (16)	.	2 (40)	2 (50)	8 (33)	1 (12.5)	6769	10286
Exhaust/supply collocated?	**No**	21	20 (95)	3 (100)	.	4 (100)	10 (100)	1 (100)	2 (67)	2 (100)	15 (100)	3 (75)	7538	11747
	Yes		1 (5)	.	.	.	.	.	1 (33)	.	.	1 (25)	1170	.
Area mixing	**Unmixed**	36	31 (86)	4 (100)	3 (100)	2 (50)	16 (84)	1 (100)	5 (100)	4 (100)	19 (79)	8 (100)	5859	9766
	Mixed		5 (14)	.	.	2 (50)	3 (16)	.	.	.	5 (21)	.	1481	2352

Ventilation rate

Table 3.5 compares the total volumetric flow rates (Q_t) and total space ventilation rates (ACM) for the 21 spaces where mechanical ventilation was observed in use.

Table 3.5. Total volumetric flow rates (Q_t) and space ventilation rates (ACM) for observations with mechanical ventilation (*n = 21*)

			Total volumetric flow rate (ft^3/min)		Total space ventilation rate (air changes per minute)		Space volume (ft^3)
		n	**Mean (SD)**	**GM (GSD)**	**Mean (SD)**	**GM (GSD)**	**Mean (SD)**
All ventilated spaces		21	895 (684)	668 (2.3)	0.78 (0.84)	0.34 (4.84)	7234 (11533)
Type of ventilation	**Exhaust**	19	894 (702)	659 (2.3)	0.79 (0.86)	0.32 (5.11)	7682 (12032)
	Dilution	2	903 (704)	753 (2.4)	0.77 (0.74)	0.57 (3.21)	2981 (3772)
Total number of blowers	**1**	17	760 (607)	569 (2.2)	0.94 (0.86)	0.44 (5.12)	5270 (10597)
	2	4	1468 (784)	1319 (1.7)	0.13 (0.08)	0.11 (1.77)	15582 (13155)
Total number of workers	**1**	11	422 (175)	393 (1.5)	0.78 (0.56)	0.42 (5.60)	6776 (14125)
	2	18	859 (629)	645 (2.3)	0.89 (0.99)	0.35 (5.50)	5968 (10019)
	≥3	7	1592 (774)	1435 (1.7)	0.48 (0.67)	0.24 (3.72)	11604 (14847)
Space volume (ft^3)	**< 1000**	11	692 (659)	485 (2.4)	1.23 (0.84)	0.97 (2.30)	582 (296)
	1000-10,000	6	1053 (499)	947 (1.69)	0.41 (0.54)	0.23 (3.97)	4857 (2561)
	>10,000	4	1214 (960)	950 (2.3)	0.05 (0.03)	0.03 (2.58)	29095 (8046)
Weld method	**SMAW**	4	1029 (846)	598 (4.8)	0.10 (1.51)	0.33 (6.62)	6089 (9517)
	TIG	3	0 (.)	0 (.)	0 (.)	0 (.)	5896 (2951)
	MIG	4	334 (93)	323 (1.4)	0.93 (0.75)	0.74 (2.13)	590 (457)
	FCAW	19	1027 (762)	831 (1.9)	0.80 (0.79)	0.36 (4.94)	8353 (13123)
	Scarfing	1	371 (.)	371 (.)	0.01 (.)	0.01 (.)	33632 (.)
	Oxy-gas	5	1240 (527)	1156 (1.6)	0.59 (0.77)	0.32 (3.89)	4712 (3110)

The total volumetric flow rates varied widely, from a low of 99 ft^3/min to a high of 2550 ft^3/min. No major differences in total flow rates are apparent between exhaust and supply ventilation ducts. The total amount of air moved within the space, however, increased with the number of blowers, the total number of workers in the space, and the volume of the space. Total flow rates were similar between SMAW, FCAW, and oxy-gas observations, although oxy-gas had slightly more air movement on average. The mean volumetric flow rate for MIG observations was approximately one-third of that for scenarios that used the SMAW, FCAW, and oxy-gas methods. The one scarfing observation had a flow rate of 317 ft^3/min, while all three TIG welding observations lacked mechanical ventilation.

The total space ventilation rate ranged from a low of 0.01 to 2.74 ACM. Total space ventilation rate did not noticeably differ between exhaust and dilution ventilation. However, ACM decreases moderately with an increase in the total number of workers in the space, and decreases dramatically with an increase in the number of blowers used and the volume of the space. Total space ventilation rate differs very little between weld methods, but is on average about twice as high for MIG scenarios when compared with SMAW, FCAW, and oxy-gas observations.

An obvious explanation for the inverse relationship between the total volumetric flow rate and the total space ventilation rate is the differences in space volume. While total air flow increases with the number of ventilation ducts and the number of total workers in the space, so too does the volume of the space. Observations that had more than one ventilation duct and more than one worker present had the highest rate of total air movement, but also had a much lower space ventilation rate since they were in significantly larger spaces. Similarly, despite the fact that MIG observations had the lowest total air flow rates, they also had the highest space ventilation rates since MIG welding, on average, was performed in much smaller spaces.

Mixing

Considering all 36 observations, 33% were characterized as having inappropriate space mixing while 67% were rated as appropriately mixed or unmixed. Only five observations reported active space mixing, two of which were mixed by air supplied to the space under the dilution observations, while the other three were mixed with a separate mixing fan.

Examining how mixing effectiveness ratings were assigned for both mixed and unmixed space provides further insight in to the rationale behind the rating designation (Table 3.6). Of the five observations where the ventilation configuration provided mixing of the air within the space, three were rated as appropriately mixed. All appropriately mixed observations were in simple confined spaces where no other worker's besides the observed welder were present, thus eliminating the possibility that mixing fume throughout the space would increase exposure to other workers. The two spaces rated as inappropriately mixed, on the other hand, was in relatively larger complex spaces other workers in the immediate area. In this case, the researcher likely concluded that mixing fume around the space increased the potential for fume exposure for the other workers and that a more appropriate ventilation strategy might have been to capture the fume near the source and exhaust it from the space.

Table 3.6. Comparison of space shape and presence of other workers with use of mixing score

		Mixed		Not mixed	
		Inappropriate *(n=2)*	**Appropriate** *(n=3)*	**Inappropriate** *(n=10)*	**Appropriate** *(n=21)*
Total other workers besides welder	**0**	.	3 (100)	6 (60)	2 (9)
	1	1 (50)	.	4 (40)	13 (62)
	≥2	1 (50)	.	.	6 (29)
Space shape	**Simple**	2 (100)	3 (100)	9 (90)	11 (53)
	Complex	.	.	1 (10)	10 (47)

A similar rationale for rating mixing is suggested when looking at differences between inappropriately not mixed and appropriately not mixed spaces. Ninety-percent of observations rated as inappropriately not mixed were in spaces with a simple geometry and free of major interior obstructions. Additionally, the majority of those spaces had no other workers in the space besides the welder and never had more than one other worker present. Conversely, nearly half of observations rated as appropriately not mixed were in complex spaces. Also, ninety percent of those spaces had workers other than the observed welder in the space at the time of the observation.

Table 3.7. Perceived ventilation effectiveness ratings for all shipyard observations (*n = 36*)

		All obs. (n/%)	Weld method (n/%)						Degree of enclosure (n/%)			Space Volume (m^3)	
			SMAW	**TIG**	**MIG**	**FCAW**	**Scarfing**	**Oxy-gas**	**Partially enclosed**	**Enclosed**	**Confined**	**Mean**	**SD**
	n=	36	4	3	4	19	1	5	4	24	8	36	
Mixing effectiveness	**Inappropriate**	12 (33)	.	.	1 (25)	9 (47)	1 (100)	1 (20)	1 (24)	9 (37.5)	2 (25)	7067	12213
	Appropriate	24(67)	4 (100)	3 (100)	3 (75)	10 (53)	.	4 (80)	3 (75)	15 (62.5)	6 (75)	4343	7419
Cross-draft effectiveness	**None**	33 (92)	3 (75)	3 (100)	4 (100)	18 (95)	1 (100)	4 (80)	2 (50)	23 (96)	8 (100)	5003	9362
	Partially effective	3 (8)	1 (25)	.	.	1 (5)	.	1 (20)	2 (50)	1 (4)	.	7973	8287
Nearest ventilation duct effectiveness	**None**	15 (42)	1 (25)	3 (100)	.	9 (47)	.	2 (40)	2 (50)	9 (37.5)	4 (50)	2473	2770
	Low	11 (30)	2 (50)	.	1 (25)	6 (32)	1 (100)	1 (20)	1 (25)	7 (29)	3 (37.5)	11566	14656
	Medium	6 (17)	.	.	1 (25)	4 (21)	.	1 (20)	1 (25)	5 (21)	.	2531	3173
	High	4 (11)	1 (25)	.	2 (50)	.	.	1 (20)	.	3 (12.5)	1 (12.5)	2379	3086
Overall ventilation effectiveness	**None**	14 (39)	1 (25)	3 (100)	.	8 (42)	.	2 (40)	2 (50)	8 (33)	4 (50)	2629	2806
	Low	13 (36)	2 (50)	.	1 (25)	9 (47)	1 (100)	.	1 (25)	10 (42)	2 (25)	9811	14047
	Medium	6 (17)	.	.	2 (50)	2 (11)	.	1 (20)	1 (25)	4 (17)	1 (12.5)	2693	3058
	High	3 (8)	1 (25)	.	1 (25)	.	.	2 (40)	.	2 (8)	1 (12.5)	2844	3604

Weld fume exposure

Of the 36 completed researcher observations, three were missing exposure values due to faulty pDR operation, resulting in 33 total operations with measured welder's breathing zone total particulate exposure, time-weighted over the length of the observation. Total observation time ranged from 4 to 18 minutes, but over 75% of observations were completed in 10 minutes. In addition to total time observed, researchers estimated how many minutes during the observation were performing hot-work, which was used to compute a percentage of total observation time spent welding (equal to: minutes spent welding/total observation minutes). On average, observed subjects welded for approximately two-thirds of the total time observed (Figure 3.3)

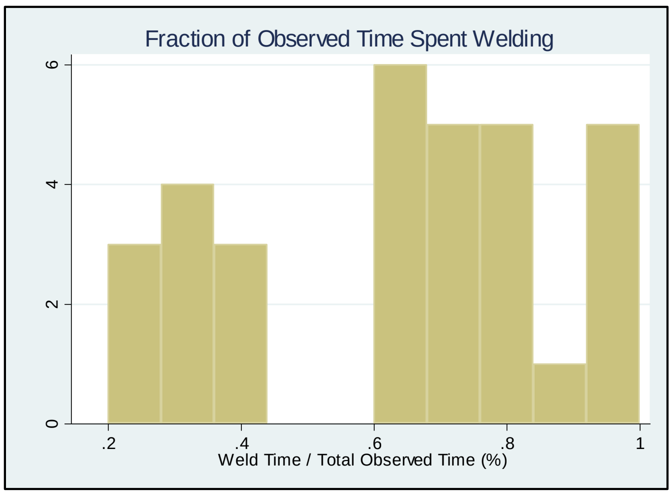


Figure 3.3. Percent of observation time spent welding (n=33).

Mean observation breathing zone concentrations were log-normally distributed across all observations. Exposure estimates were left untransformed in the following comparison of exposure and weld method; for all subsequent analysis exposure data were transformed by taking the natural logarithm of each mean observation breathing zone concentration.

Exposure and work, space, and ventilation characteristics

Average breathing zone total particulate concentrations varied significantly by the weld method used (Table 3.8; Figure 3.4). Excluding scarfing, welders using the FCAW method had the highest mean breathing zone total particulate concentrations, with roughly 35% of those observations in excess of 5.0 mg/m^3.

Welder's using the stick, MIG, and oxy-gas methods had similar exposure estimates. For all three methods the average observation concentrations were approximately 1.0 mg/m^3, and maximum observation exposures approached but never exceeded 2.5 mg/m^3.
The average breathing zone concentration of total particulate was low for all three TIG observations, with a maximum breathing zone total particulate concentration of less than 0.4 mg/m^3.

Table 3.8. Welder breathing zone total particulate concentration by weld method (*n = 33*)

Weld method	n	Breathing zone TP concentration (mg/m^3) Mean	SD	Min.	Max.
Stick	4	1.2	1.1	0.1	2.2
TIG	3	0.2	0.2	0.1	0.4
MIG	3	1.1	1.2	0.1	2.4
FCAW	17	7.1	12.0	0.9	50.2
Scarfing	1	47.1	.	47.1	47.1
Oxy-gas	5	0.9	1.0	0.2	2.5

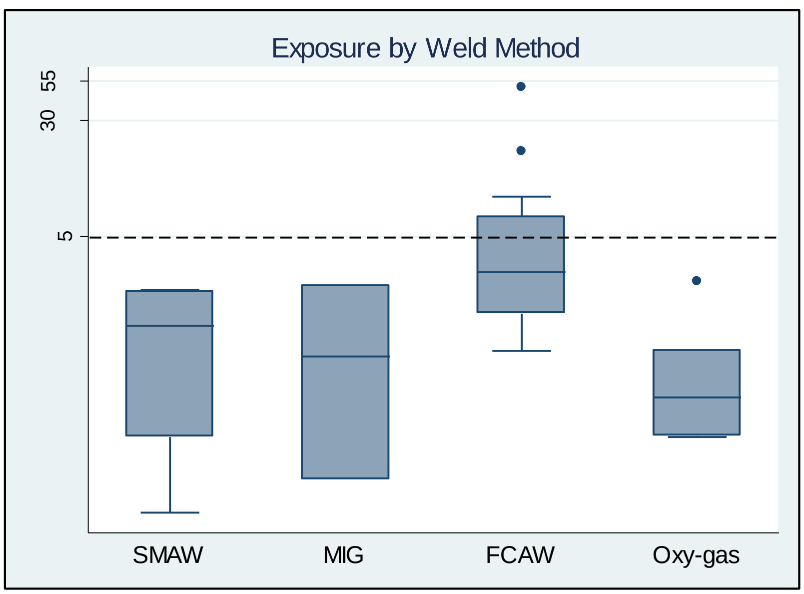


Figure 3.4. Mean breathing zone total particulate concentration by weld method. Dashed line denotes Washington State PEL for total welding fume of 5.0 mg/m^3 (WAC, 2007). Y-axis on log scale.

Considering that similar fume generation rates are reported for the MIG and stick welding methods (AWS, 1987) and that measured breathing zone concentrations for MIG and stick observations were similar in magnitude, the two methods were combined as a single welding category for all subsequent analysis. Additionally, there was very little variation in work, space, and ventilation characteristics between the three TIG observations, so those were excluded in the analysis that compares exposure with observation form parameters. Lastly, the scarfing method had only one observation, so that observation was also dropped from the analysis. Table 3.9 compares the log-transformed average breathing zone particulate concentrations for the remaining observations with space, work, ventilation, and perceived effectiveness.

Mean exposure tends to increase with the degree of space enclosure for both FCAW and SMAW/MIG observations; however confined space observations have the lowest mean exposure for the oxy-gas method. Welders performing new construction work have higher average exposures than those performing repair work, although this is likely due to the fact that new construction spaces where on average much smaller than repair work spaces, with mean volumes of 208 ft^3 and 6691 ft^3, respectively. Interestingly, the opposite effect is shown when observations are categorized by space; average welder exposure in spaces smaller than 1000 ft^3 are roughly half of those in spaces ranging from 1000 ft^3 to 33,000 ft^3. Not surprisingly, breathing zone fume concentrations tended to be higher in observations where the welder was wearing a respirator, supporting the anecdotal observation that workers were more likely to don respiratory protection when high amounts of weld fume was present in the space.

Table 3.9. Measured breathing zone total particulate concentration (mg/m^3) by weld method and for all observations compared with space and work characteristics ($n = 29$)

		FCAW			SMAW and MIG			Oxy-gas welding/cutting		
		n	**GM**	**GSD**	***n***	**GM**	**GSD**	***n***	**GM**	**GSD**
	All observations	17	3.6	3.0	7	0.6	4.3	5	0.5	2.8
Degree of enclosure	**Partially enclosed**	1	2.2	.	2	0.9	3.4	1	2.5	.
	Enclosed	13	3.0	3.1	4	0.4	5.1	0	.	.
	Confined	3	8.5	2.0	1	2.1	.	4	0.4	1.9
Space shape	**Simple**	15	3.6	3.2	6	0.6	4.8	3	0.8	3.3
	Complex	2	3.3	1.8	1	0.4	.	2	0.3	1.5
Type of work	**New construction**	6	1.6	1.9	0	.	.	2	0.2	1.0
	Repair	11	5.5	2.8	7	0.6	4.3	3	1.0	2.5
Space size	**Small (30-1000 ft^3)**	8	2.3	2.7	5	0.5	5.1	2	0.2	1.0
	Medim (1000-6000 ft^3)	6	5.8	3.5	1	0.4	.	2	1.0	3.5
	Large (6000-33000 ft^3)	3	4.2	1.8	1	2.2	.	1	0.9	.
Proximity of head to plume	**In plume**	6	4.5	1.7	.	.	.	0	.	.
	Near plume	9	4.0	3.8	3	0.8	5.4	1	0.2	.
	Away from plume	2	1.2	1.3	4	0.5	4.4	4	0.7	2.8
Respirator used?	**No**	4	2.2	2.6	2	0.2	5.5	3	0.6	3.5
	Yes	13	4.2	3.0	5	0.9	3.9	2	0.4	2.6
Total # of other workers in space	**0**	8	2.0	2.2	1	0.8	.	1	0.2	.
	1	7	7.2	3.2	6	0.6	4.9	2	0.4	2.6
	> 1	2	3.6	1.2	0	.	.	2	1.0	3.5

No obvious trends between exposure and the type of ventilation used were observed. In fact, for all weld methods combined and for the oxy-gas method, exposures were lower in observations with no ventilation when compared to exhaust ventilation. For FCAW welders, exposure was greatest when using no mechanical ventilation, followed by exhaust ventilation, and then by the mean exposure for the two FCAW configurations that used dilution ventilation. No obvious differences in exposure were noted when comparing the proximity of the nearest exhaust duct, although the average exposure for the two observations that used LEV were lower than the exposures for REV and GEV configurations. Welding in dead space did not seem to increase exposure, in fact, "dead space" welders had lower mean breathing zone fume concentrations for both SMAW/MIG and oxy-gas observations. Also, exposures were higher with a breathing zone cross-draft and lower with collocation of the exhaust and supply points, although the low frequency with which those configurations were observed limits the interpretation. Actively mixing the air within the space, however, did seem to reduce fume concentration in the breathing zone. For both FCAW and SMAW/MIG observations unmixed spaces had welder exposures approximately twice as high as welders in mixed spaces.

As previously described, the total amount of airflow in the space is likely less important than the amount of air moved relative to the size of the space. This effect is suggested by the fact that average welder exposures across all weld methods increased with the volumetric ventilation rate (Q), but decreased with the space ventilation rate (ACM).

Table 3.10. Measured breathing zone total particulate concentration (mg/m^3) by weld method and for all observations compared with observed use of ventilation (*n = 29*)

		FCAW			SMAW and MIG			Oxy-gas welding/cutting		
		n	**GM**	**GSD**	**n**	**GM**	**GSD**	**n**	**GM**	**GSD**
	All observations	17	3.6	3.0	7	0.6	4.3	5	0.5	2.8
Type of ventilation	**No ventilation**	9	4.1	3.9	1	0.4	.	2	0.2	1.0
	Exhaust	6	3.3	2.2	6	0.6	4.8	3	1.0	2.5
	Dilution	2	2.4	2.1	0	.	.	0	.	.
Proximity of nearest exhaust duct	**Local**	.	.	.	2	0.4	11.9	0	.	.
	Regional	.	.	.	1	0.8	.	1	0.9	.
	General	6	3.3	2.2	3	0.8	5.4	2	1.0	3.5
Weld in deadspace?	**In dead-space**	15	3.7	3.2	2	0.9	3.4	3	0.3	1.4
	Not in dead-space	2	3.0	1.0	5	0.5	5.1	2	1.5	2.1
Breathing zone cross-draft?	**No cross-draft**	16	3.6	3.1	6	0.5	4.3	4	0.4	1.9
	Cross-draft	1	2.7	.	1	2.2	.	1	2.5	.
Exhaust/supply collocated?	**Not collocated**	8	3.1	2.1	6	0.6	4.8	2	1.5	2.1
	Collocated	1	1.5	.	0	.	.	1	0.4	.
Area Mixing	**Unmixed**	14	4.0	3.1	5	0.8	4.7	5	0.5	2.8
	Mixed	3	2.1	1.8	2	0.3	3.8	0	.	.
Volumetric flow rate (Q_t)	**Low (90-1000 ft^3/min)**	5	2.9	2.6	4	0.4	5.1	1	2.5	.
	High (1100-2550 ft^3/min)	3	3.2	1.2	2	2.2	1.0	2	0.6	1.7
Space ventlation rate	**Low (0.01-0.50 ACM)**	5	4.6	1.6	4	0.7	5.1	2	1.5	2.1
	High ACM (1.0-2.8 ACM)	3	1.5	1.7	2	0.5	7.8	1	0.4	.

Exposure and perceived ventilation effectiveness

Subjective researcher ratings of how well the space mixing reduced the potential for fume exposure is not evidenced by the exposure measurements (Table 3.11). Average breathing zone fume concentrations were higher across all observations rated as appropriately mixed/unmixed when compared to configurations designated as inappropriately mixed/unmixed. Similarly, all three breathing zone cross-drafts observed were rated as partially effective, but as indicated earlier welders in those observations had higher exposure measurements than those without cross-draft airflows across each weld method category.

Assessments of the effectiveness of the nearest ventilation duct to the weld and the overall use of ventilation effectiveness matched fairly well with exposure. When looking just at observations where mechanical ventilation was used breathing zone fume concentration decreases with both individual duct and overall effectiveness ratings across all weld methods. For FCAW observations, exposure was highest when no ventilation was used. Conversely, SMAW/MIG and oxy-gas welders had lowest mean exposures under configurations where no ventilation was used.

Table 3.11. Measured breathing zone total particulate concentration (mg/m^3) by weld method and for all observations compared with reseracher percieved ventilation effectiveness scores (n=29)

		FCAW			*SMAW and MIG*			*Oxy-gas welding/cutting*		
		n	**GM**	**GSD**	***n***	**GM**	**GSD**	***n***	**GM**	**GSD**
	All observations	17	3.6	3.0	7	0.6	4.3	5	0.5	2.8
Mixing effectiveness	**Inappropriate**	9	3.4	3.6	1	0.1	.	1	0.2	.
	Appropriate	8	3.8	2.4	6	0.8	4.0	4	0.7	2.8
Cross-draft effectiveness	**None**	16	3.6	3.1	6	0.5	4.3	4	0.4	1.9
	Partially effective	1	2.7	.	1	2.2	.	1	2.5	.
Nearest ventilation duct effectiveness	**None**	9	4.1	3.9	1	0.4	.	2	0.2	1.0
	Low	5	3.7	2.4	2	2.2	1.0	1	0.4	.
	Medium	3	2.2	1.5	1	0.1	.	1	2.5	.
	High	0	.	.	3	0.5	6.0	1	0.9	.
Overall ventilation effectiveness	**None**	8	4.7	4.0	1	0.4	.	2	0.2	1.0
	Low	7	2.8	2.3	2	2.2	1.0	0	.	.
	Medium	2	2.8	1.1	2	0.3	3.8	2	1.0	3.5
	High	0	.	.	2	0.4	11.9	1	0.9	.

Exposure Modeling

A multiple regression analysis was performed to evaluate the relationship between measured exposure and variables associated with the recommended ventilation guidelines, after controlling for the weld method used and the percentage of the time spent welding. Each observation form variable was added to the alternate regression model one at a time and compared to the base model which included only the three category weld method variable and the continuous time spent welding variable (Equation 3.1; Table 3.12).

Equation 3.1. Base model:

$$\boldsymbol{ln}(\boldsymbol{total\ particulate\ exposure}) = \boldsymbol{\alpha} + \boldsymbol{\beta}[\boldsymbol{weld\ method}] + \boldsymbol{\beta}[\%\ \boldsymbol{time\ welding}] + \boldsymbol{\varepsilon}$$

Table 3.12. Base model ($r^2 = 0.32$)

	Coeff.	**SE**	**p**	**95% CI**
Intercept	-0.8	0.7	0.26	[-2.2, 0.6]
SMAW/MIG	-	-	-	-
Oxy-gas	-0.3	0.8	0.71	[-1.9. 1.3]
FCAW	1.7	0.5	< 0.01	[0.6, 2.8]
Weld time	0.5	1.0	0.60	[-1.6, 2.6]

Weld method was included in the base model since it was identified in the univariate analysis as likely the most important determinate of weld fume exposure. While time spent welding did not significantly contribute to the prediction of exposure, it was included based on the *a priori* assumption that the actual time welding was directly related to the weld fume emission and therefore the potential for exposure. FCAW welding was the only statistically significant predictor of total particulate breathing zone concentration, while oxy-gas was not significantly different from the SMAW/MIG reference category.

Likelihood-ratio tests were performed for each base model-alternate model comparison to see if the addition of any of the ventilation-related variables significantly contributed to the prediction of total particulate exposure (Table 3.13).

Table 3.13. Results from likelihood ration tests comparing base model (weld method + percentage of time spent welding) with each ventilation-related observation form variable

Variable added in alternate regression model: (variable catergories)	***n***	**LRT p**
Degree of space enclosure (partially enclosed, enclosed, confined)	29	0.13
Space size (Small [30-1000ft^3], medium [1000-6000ft^3], large [6000-30000ft^3])	29	0.08
Proximity of welder's head to plume (In plume, near plume, away from plume)	29	0.43
Type of ventilation (No ventilation, exhaust, diluition)	29	0.75
Proximity of nearest exhaust duct to weld (Local, regional, general)	17	0.74
Position of weld relative to airflow (In dead space, not in deadspace)	29	0.80
Position of weld relative to airflow (if mechanically ventilated) (In dead space, not in deadspace)	17	0.82
Space ventilation rate (ACM) (Low [0.01-0.50 ACM], High [1.0-2.8 ACM])	17	0.08
Use of mixing (Unmixed, mixed)	29	0.15
Mixing appropriatelness score (Appropriate, Inappropriate)	29	0.22
Overall score (No ventilation, low, medium, high)	29	0.98
Overall score (if mechanicaly ventilated) (Low, medium, high)	17	0.33

No ventilation-related variables significantly contributed to the prediction of total particulate exposure at the 0.05 significance level. Several variables, however, were close to significance, falling within an arbitrarily set confidence level of 0.15, including the degree of enclosure, the space size, the observed use of mixing, and the space ventilation rate. Space size, mixing, and ventilation rate variables were added to the multiple regression model one at a time to evaluate the trends between categorical levels of each of those variables and estimated breathing zone exposure (Table 3.14).

Table 3.14. Results of multiple regression comparing base model to base model with addition of space size, space ventilation rate, and use of mixing variables. Values in units of ln(mg/m3)

		Coeff.	SE	p	95% CI
Base model (r^2 = 0.32):	Intercept	-0.8	0.7	0.26	[-2.2, 0.6]
	SMAW/MIG	-	-	-	-
	Oxy-gas	-0.3	0.8	0.71	[-1.9. 1.3]
	FCAW	1.7	0.5	< 0.01	[0.6, 2.8]
	Weld time	0.5	1.0	0.60	[-1.6, 2.6]
+ Space size (r^2 = 0.40):	Intercept	-0.3	0.7	0.63	[-1.8, 1.1]
	SMAW/MIG	-	-	-	-
	Oxy-gas	-0.1	0.8	0.90	[-1.6, 1.5]
	FCAW	1.6	0.5	0.01	[0.5, 2.7]
	Weld time	-1.0	1.2	0.43	[-3.5, 1.5]
	Small	-	-	-	-
	Medium	1.1	0.6	0.07	[-0.1, 2.3]
	Large	1.2	0.7	0.10	[-0.2, 2.6]
+ Space ventilation rate (r^2 = 0.27):	Intercept	-0.1	1.0	0.93	[-2.3, 2.1]
	SMAW/MIG	-	-	-	-
	Oxy-gas	0.5	1.2	0.72	[-2.2, 3.1]
	FCAW	1.6	0.8	0.07	[-0.2, 3.4]
	Weld time	-0.1	1.8	0.96	[-4.0. 3.9]
	Low ACM	-	-	-	-
	High ACM	-0.9	0.6	0.14	[-2.1. 0.3]
+ Use of mixing (r^2 = 0.31):	Intercept	-0.6	0.7	0.40	[-2.0, 0.8]
	SMAW/MIG	-	-	-	-
	Oxy-gas	-0.5	0.8	0.51	[-2.2, 1.1]
	FCAW	1.6	0.5	0.01	[0.5, 2.8]
	Weld time	0.6	1.0	0.56	[-1.5, 2.7]
	Unmixed	-	-	-	-
	Mixed	-0.8	0.6	0.20	[-2.0, 0.4]

Positive regression coefficients for medium and large space size when compared to the reference small space size category suggest that exposure tends to increase with the volume of the space. While counterintuitive, these results are consistent with the trends identified in the previous univariate analysis and can likely be explained by the inverse relationship between space volume and space ventilation rate. When space ventilation rate is added to the mode, a decrease in exposure is seen in spaces with a high ventilation rate (ACM between 1.0 and 2.8) when compared to relatively poorly ventilation spaces (ACM between 0.1 and 0.5); although the difference is not statistically significant at the 0.05 confidence level.

Lastly, when the use of mixing variable is added to the regression model predicted breathing zone exposure is lower is actively mixed spaces when compared to the reference unmixed category. Again, this is consistent when the trends identified in the univariate analysis, although not statistically significant.

Discussion

The primary aim of conducting the shipyard observations was to evaluate the observational tool as a method for measure ventilation-related behavior as defined by the recommended guidelines. Despite the small number of side-by-side observations performed, inter-observer reliability for the majority of the observation questions was good. Relatively low agreement between raters was demonstrated for characterizations of the position of the weld relative to the ventilation airflow (dead-space), and assigning a mixing appropriateness rating. In theory, observing where the weld is in relation to the air movement is simple; however, in actual practice it was often difficult to determine whether or not the weld position was within the effective "reach" of the ventilation. Additionally, determining if the use of area mixing techniques was appropriate given the space and work characteristics was difficult, given the fact that the recommended use of mixing as expected by the recommended guidelines was often not easily applied to real-work scenarios. Revisiting the dead-space and mixing appropriateness ratings is recommended in order to establish a more objective and consistently followed reporting criteria among observers. Also worth noting is that all spaces that lacked mechanical ventilation received an overall effectiveness rating of "zero/none." As previously demonstrated, there were large differences in the potential for fume exposure between non-ventilation related determinants, such as the weld method and size of the space. In the future, the study staff might consider more specifically evaluating spaces with no ventilation in terms of exposure potential.

Evaluating the validity of the recommended ventilation guidelines was addressed by comparing measuring welder exposure to the observed use and perceived effectiveness of the ventilation configurations currently employed by the welders at the study shipyard. Both the univariate and multi-regression analysis identified trends between exposure and the use of the recommended guidelines; however, due the small number of observations with exposure measurements ($n=29$), making confident conclusions regarding the relationship between exposure and ventilation use is not warranted. The observation configurations compared varied not only in the use of ventilation, but also in other key determinants of exposure such as the weld method and space characteristics; therefore those factors had to be controlled for in the analysis. Confounding the issue was the low frequency of the observed use of the recommended guidelines. For example, dilution ventilation and breathing zone cross-drafts were only observed two and three times, respectively, making meaningful comparisons challenging. Moving forward, it is recommended that the shipyard observations be continued in order to build the dataset and further evaluate the relationship between exposure and ventilation-related behavior. In addition, the study staff might consider manipulating the ventilation within a space in order to evaluate specific techniques of interest while at the same time “controlling” for other determinants of exposure not directly related to the use of ventilation. In this way, the validation of the guidelines could be expedited and the observation method could be used primarily as a way of measuring ventilation-related behavior independent of exposure.

Another limitation to this study design was the short observation time. Most observations were completed in 10 minutes or less. The effects of some of the recommended practices, however, might not be evident in such a short time frame. For example, the intervention training teaches that REV is more effective at fume control than GEV. Exposures in the near field (breathing zone), however, are not expected to be significantly different between the two exhaust locations. REV is recommended based on the premise that it is closer to the area of high concentration and thus removes more fume and reduces the potential for accumulation over time. If the observation is completed within 10 minutes of the start of the weld, however, this reduction in area concentration would likely not be evident. Alternatively, if the observation time was increased a more comprehensive understanding of the general ventilation techniques perform and compare throughout the work day.

The investigation of the use of the overall ventilation effectiveness score also highlighted improvements that can be made in future observation method use. The overall score was used as an aggregate summary how close actual observed ventilation use was to the "ideal" state that would be expected given full adoption of the ventilation guidelines. However, in practice the overall score was mostly dominated by the proximity of the nearest exhaust duct, the weld method, and our assessment to whether the weld was in airflow dead-space. In hind-sight, it might have been more information to complete a detailed physical description of the work task and space and then after the sampling day specifically identify what the "ideal" ventilation configuration would be. In that way, the study team would have an overall score with greater resolution that could be used to more accurately compare ventilation use and exposure.

Performing a baseline assessment of the use of ventilation has provided insight in to the work shipyard welders perform and how they currently use ventilation. One surprise that should be noted is that shipyard welding is not nearly as dynamic as the research team had predicted at the onset of this project. Welding in enclosed and confined spaces was more difficult to encounter than originally anticipated. The most productive day of sampling resulted in four researcher observations, but on most sampling days only one or two observations were completed. Welders rarely moved between multiple work spaces in the same day, and sometimes welded in the same space for weeks-on-end. The relatively slow pace of welding work could be explained by the fact that for the majority of the survey time no new construction was occurring. In future work, the fact that welders spend a relatively long time in each space could be taken advantage of by increasing the observation time for the reasons previously mentioned.

Currently, the welders at the surveyed shipyard do not follow most of the guidelines that are recommended by the intervention training. Nearly half of all observed welding tasks were performed in the absence of mechanical ventilation. When ventilation was present, it was almost always a GEV duct placed haphazardly in the space, regardless of the space size or configuration. Many times, collapsible plastic ducting ("lay-flat") was used instead of reinforced ducting, requiring that the blower be placed within the space. When this configuration was used, the exhaust intake was usually placed on the bottom of the space and not nearby the weld, rendering the ventilation virtually obsolete at controlling breathing zone fume concentrations. One simple recommendation that could be added to the intervention training would be to also use reinforced ducting so that the intake can be placed at a point above the weld and as close to the weld as possible. Additionally, while the total flow rate through the ventilation ducts general increased with the volume of the space (as recommended), the increase was general not sufficient enough to effectively ventilation the space. In very large spaces, therefore, shipyard welders should be encouraged to use techniques not dependent on the volume of the space, such as exhausting air near the weld and generating a breathing zone cross-draft.

Dilution ventilation was only observed twice during the survey period. In both cases, the supply of fresh air to the space seemed to be done primarily as a means of preventing the buildup of inert weld shielding gases. Despite the inability to clearly assess the relationship between dilution ventilation and exposure with the observation data, the method could likely play a major role in effectively ventilating simple shipyard enclosed spaces when other workers are not present.

Current use of area mixing and breathing zone cross-draft ventilation techniques is limited. Only five welding tasks that used active space mixing were observed, all of which were in relatively small simple spaces. The average welder exposure for mixed spaces was on average lower than unmixed spaces within the same weld method categories. Considering that along with the high frequency of simple unmixed spaces suggests that space mixing is also a technique that could be effectively implemented. However, future intervention trainings should stress the point that mixing fume around the space should only be done if it does not increase the exposure potential for other workers.

All three breathing zone cross-drafts observed were the incidental effect of natural ventilation and the position of the weld. The distribution of the three cross-draft observations across three different weld methods combined with the lack of variation in the cross-draft effectiveness rating made for any comparison with exposure difficult. However, it should be noted that none the welding methods used when a cross-draft was reported (flux core, stick, and oxy-gas cutting) are supplied with an independent shielding gas (like the MIG and TIG methods), and are thus more resilient to reduced weld qualities resulting from turbulent air movements. In fact, shipyard welders have commented on how they will sometimes use their bodies to block any natural air currents in order to preserve weld quality while using the MIG and TIG methods. The study staff should consider how the need to preserve weld quality might affect the successful implementation of area mixing and cross-draft techniques.

One benefit to the rare current use of recommended ventilation practices is that it suggests a great potential for impact of the intervention trainings. The baseline characterization of ventilation use identified many small, simple, welder-only spaces that could be more effectively ventilated by using area mixing or general dilution techniques. Also, the results have shown that there exist many large enclosed spaces that may not be effectively ventilation by general ventilation, indicating opportunities where near-field techniques such as the use of a breathing zone cross-draft might could be implemented. Additionally, the fact that nearly one-half of all welders performed in the presence of mechanical ventilation were characterized as being in airflow dead space suggests that reinforcing the importance of configuration the ventilation so that the weld is within the path of ventilation airflow could positively impact the effective use of ventilation in these spaces.

Conclusions

The work conducted in this thesis has demonstrated that the observational tool is a reliable method for measuring ventilation-related behavior as defined by the guidelines, although a reevaluation on the reporting criteria for assessing welding in airflow dead-space and determining the appropriate use of area mixing is warranted. Additionally, the analysis comparing welder breathing zone total particulate exposure and the use of ventilation suggests that the adoption of the recommended guidelines might reduce the potential for welding fume exposure, however additional observation measurements are needed to more confidently evaluate the relationship.

The characterization of baseline use of ventilation by welders in the study shipyard has demonstrated that welder's do no currently use ventilation very effectively, at least as defined by the recommended guidelines and as evidenced by their measured exposure. Recommended practices such as dilution ventilation, area mixing, and breathing zone cross-draft airflow are rarely if ever used, suggesting there exists a great potential for impact of the intervention training. Additionally, the welders at the study shipyard performed work without respiratory protection approximately one-third of the time, regardless of the weld task of task specifics, which highlights the limitations of relying solely on personal protection equipment and strengthens the argument for effective ventilation.

In general, the work conducted towards this thesis suggests that the observational method is a reliable way to measure ventilation-related behavior. However, due to the sporadic nature of enclosed/confined space welding during the study period, the current approach might not be the most efficient way of validating the effectiveness of the recommended practices. Lessons learned from this work can be used by study staff in inform project future efforts, such as the recommendation that validation of the guidelines be accomplished by implementing specific ventilation techniques in actual shipyard welding scenarios, and that changes in ventilation-related behavior post-intervention be evaluated independent of measured exposure.

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APPENDIX A: Side-by-side controlled chamber pDR comparison data

Comparisons made at the time of the controlled ventilation experiments (June 3, 2011):

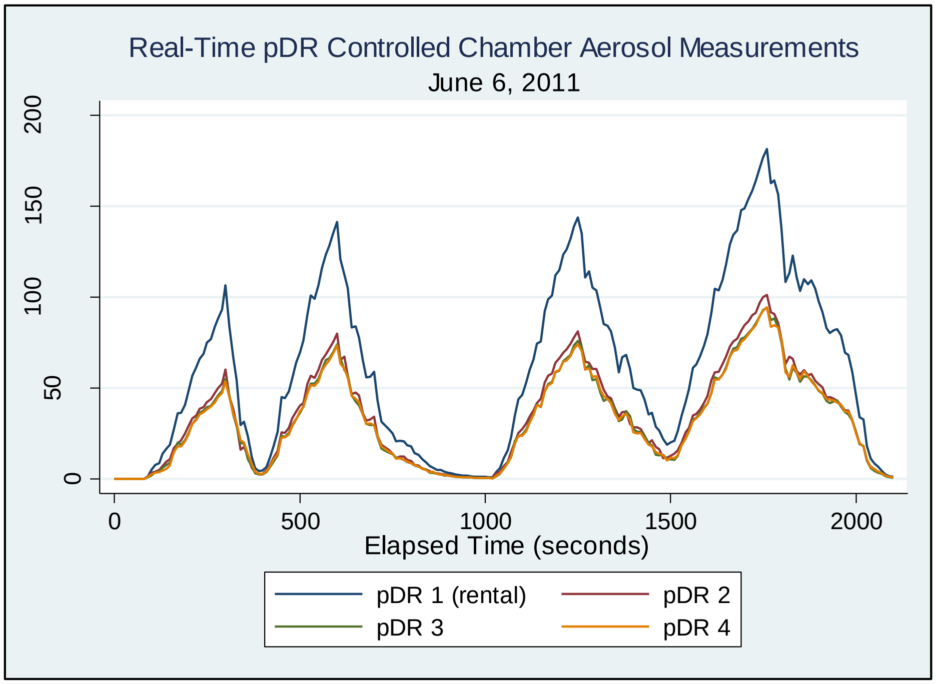


Figure A.1. Real-time particulate measurements for all ventilation experiment particulate monitors measuring side-by-side in controlled exposure chamber.

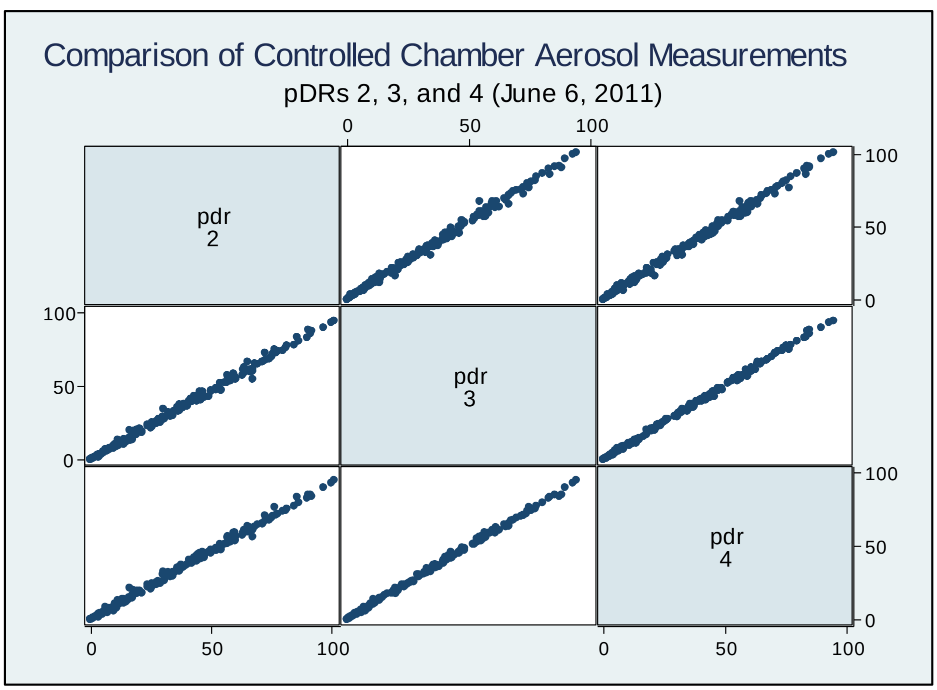


Figure A.2. Scatter plot matrix comparing real-time measurements for pDRs 2, 3 and 4. For all comparisons slope coefficient between 0.95 and 1.05.

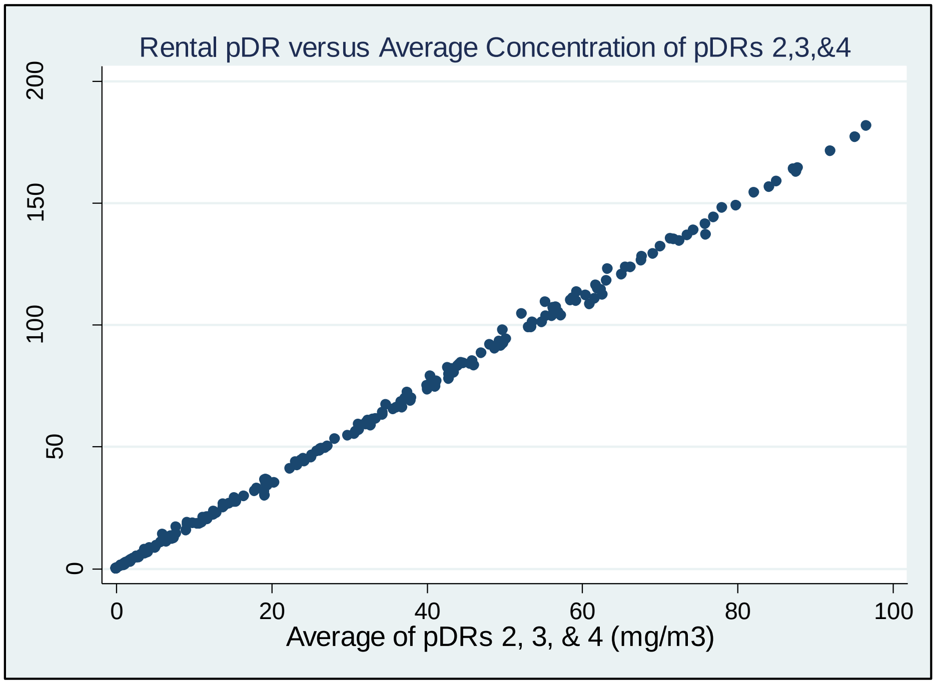


Figure A.3. Real-time concentration from rental unit versus the average concentration measured by pDRs 2, 3, and 4. Regression equation used to adjust measured concentration from rental unit: (Adjusted Concentration) = 0.534 (Rental pDR measured Concentration).

Comparisons made at the time of shipyard observations (April 19, 2012):

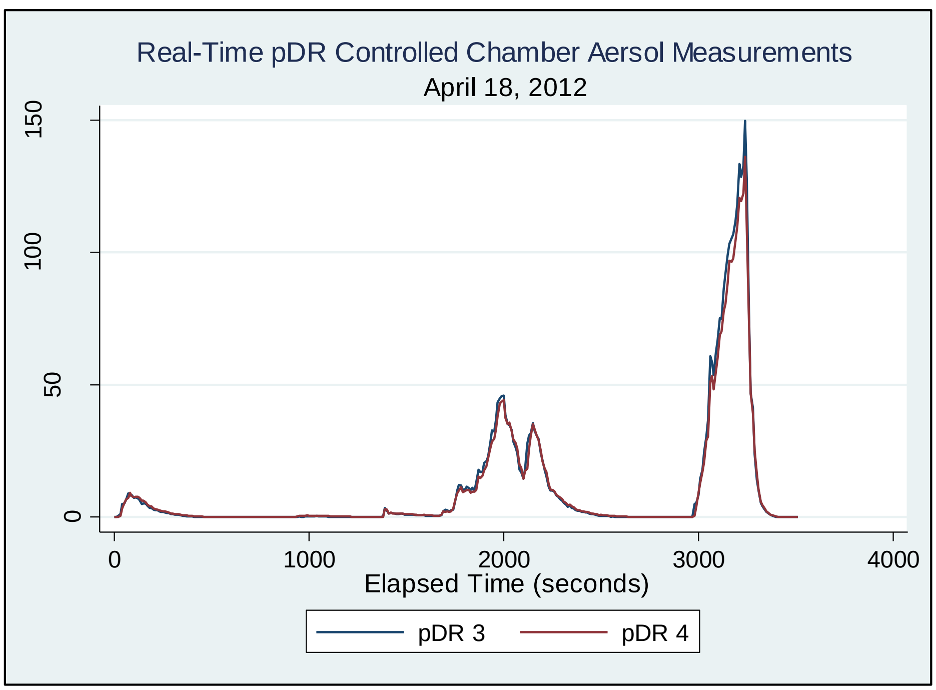


Figure A.4. Real-time particulate measurements for all ventilation experiment particulate monitors measuring side-by-side in controlled exposure chamber.

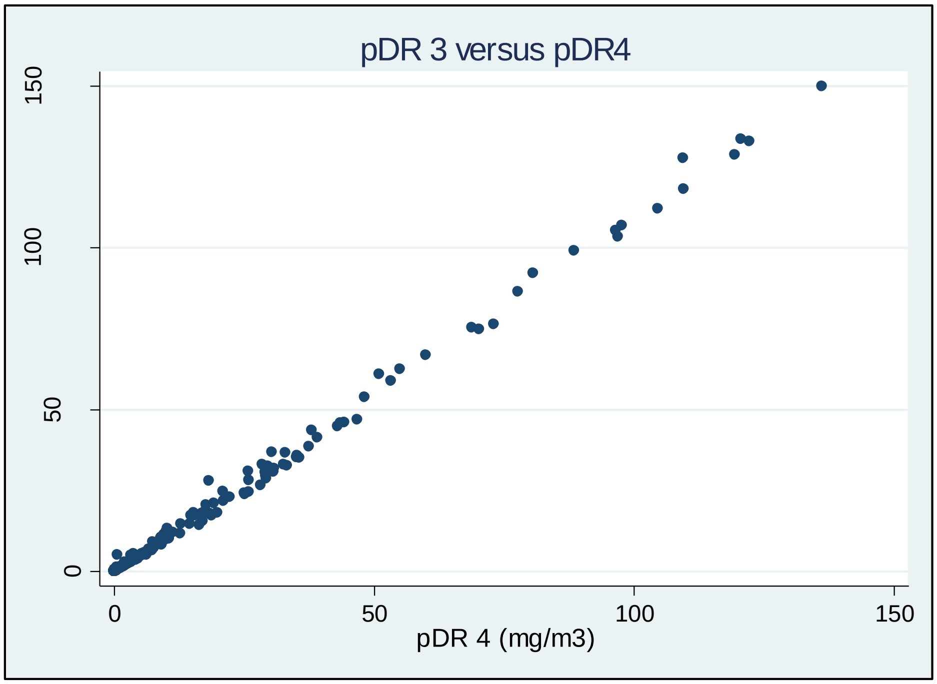
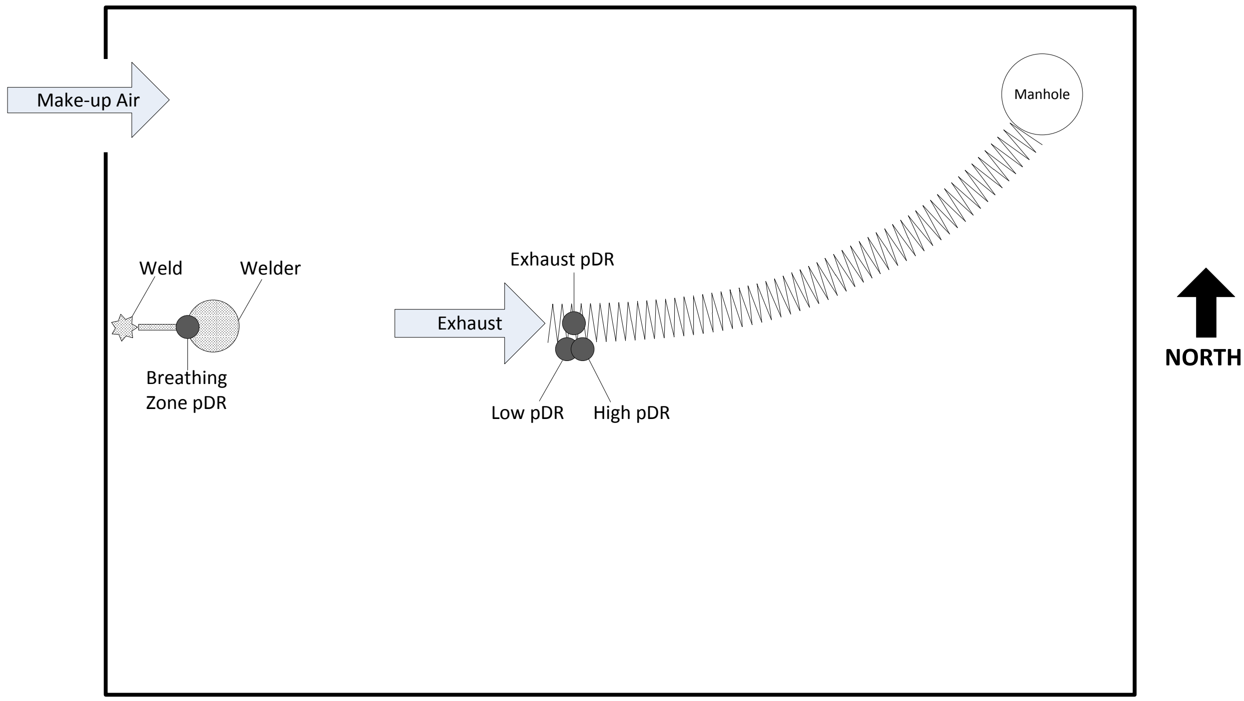


Figure A.5. Real-time concentration for pDR 3 versus pDR 4. Slope coefficient = 1.04.

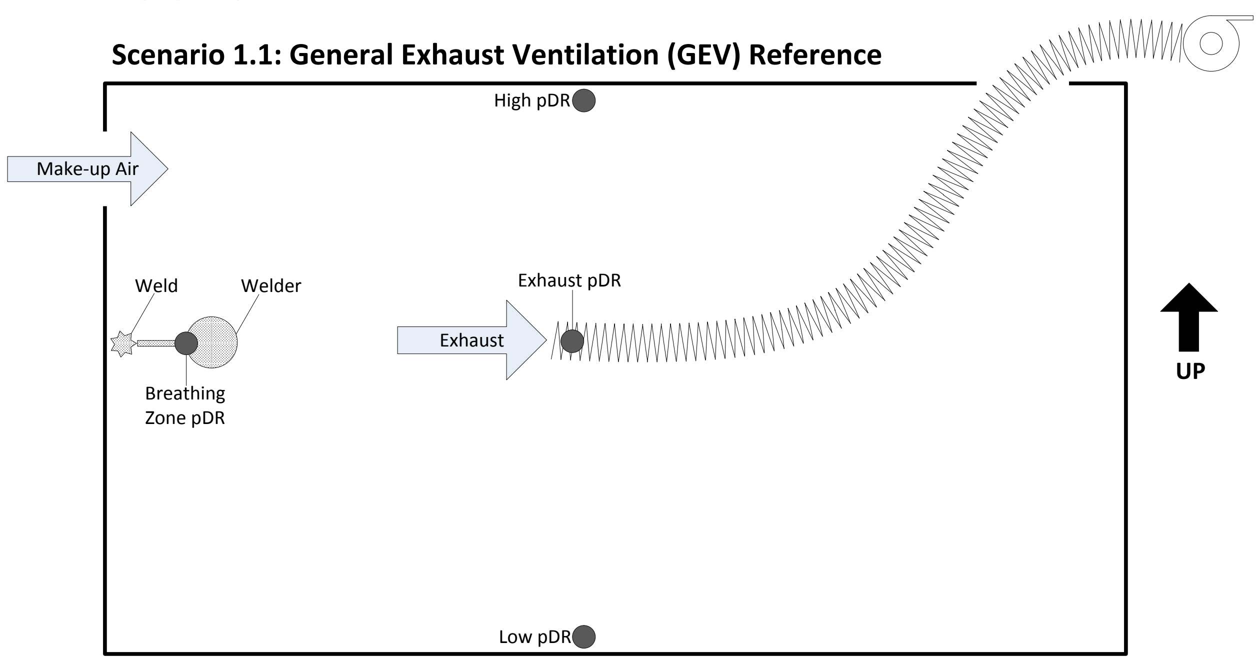
APPENDIX B: Experimental Scenario Schematics

Scenario 1.1: General Exhaust Ventilation (GEV) Reference



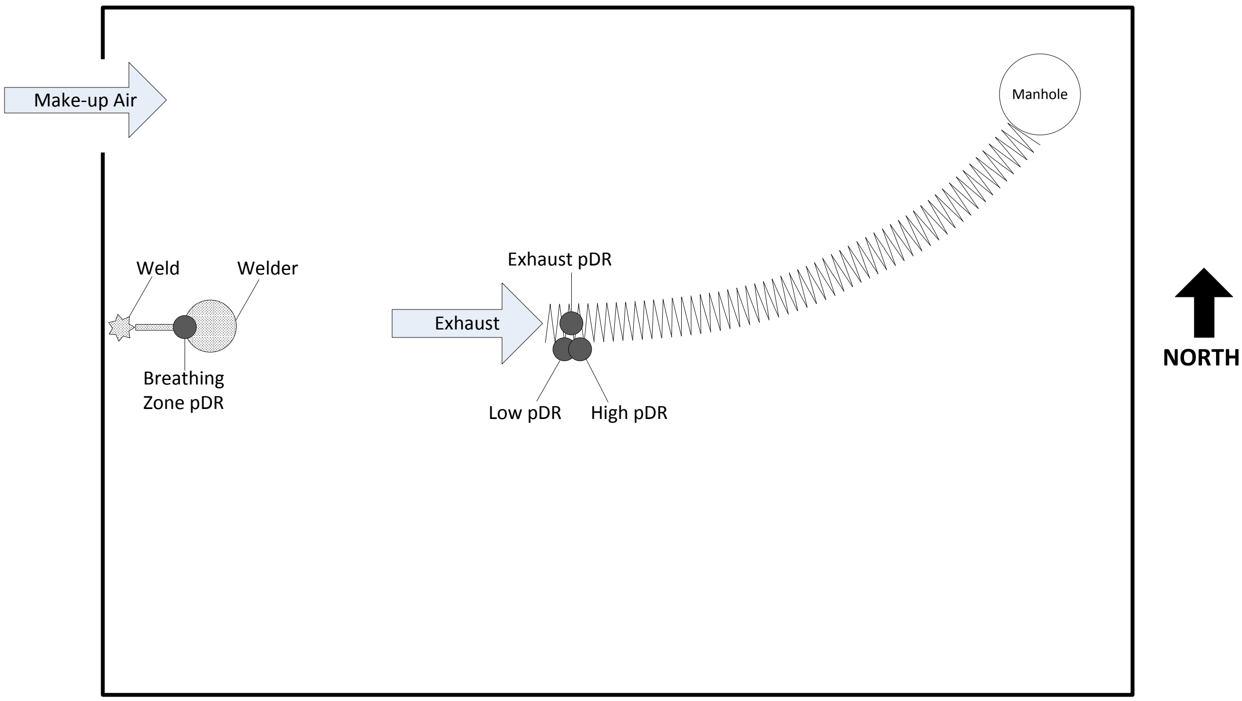
Aerial View

Scenario 1.1: General Exhaust Ventilation (GEV) Reference



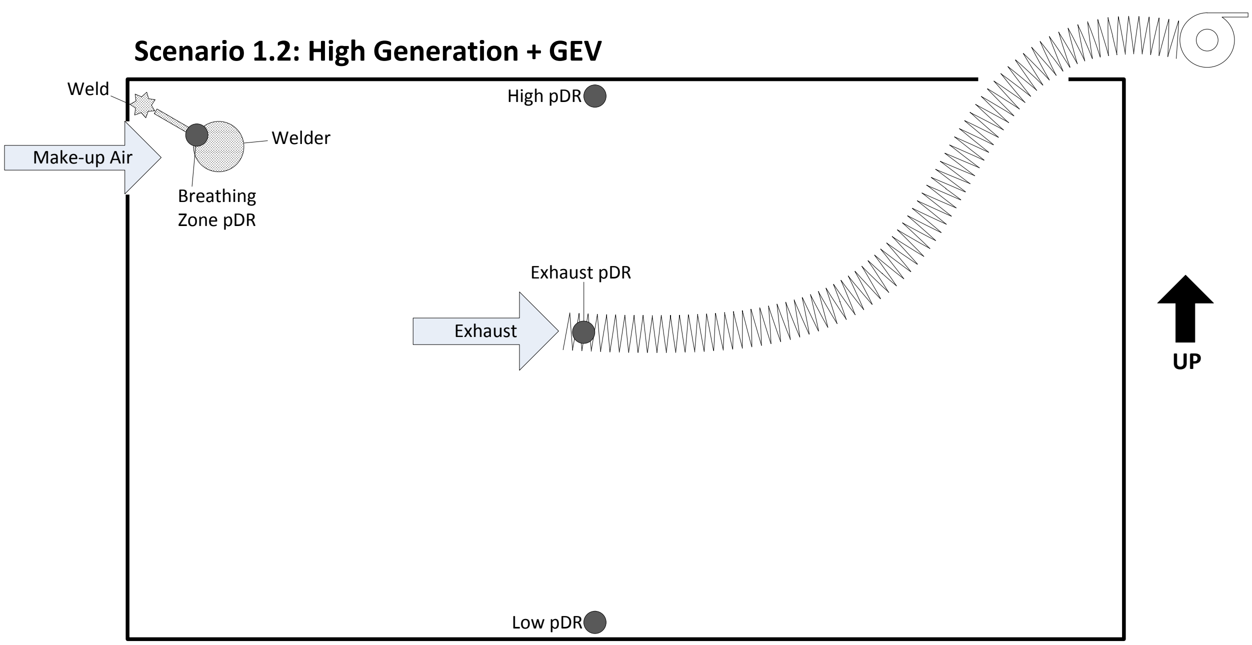
Lateral View

Scenario 1.2: High Generation + GEV



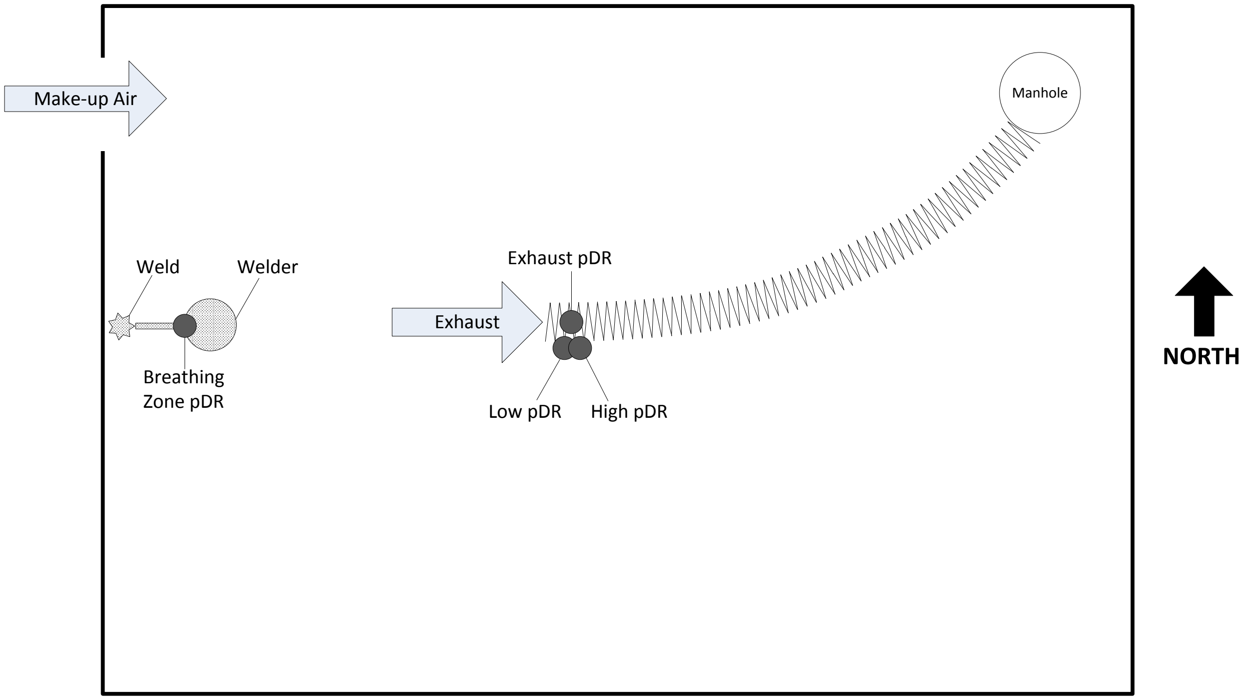
Aerial View

Scenario 1.2: High Generation + GEV



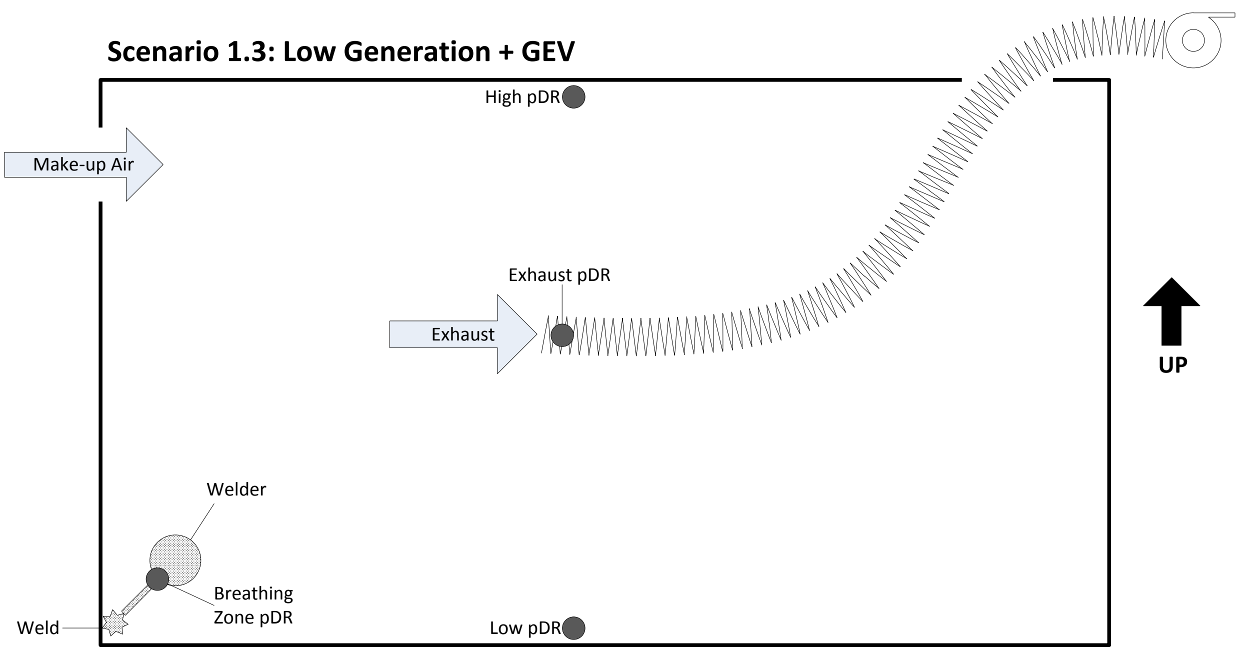
Lateral View

Scenario 1.3: Low Generation + GEV



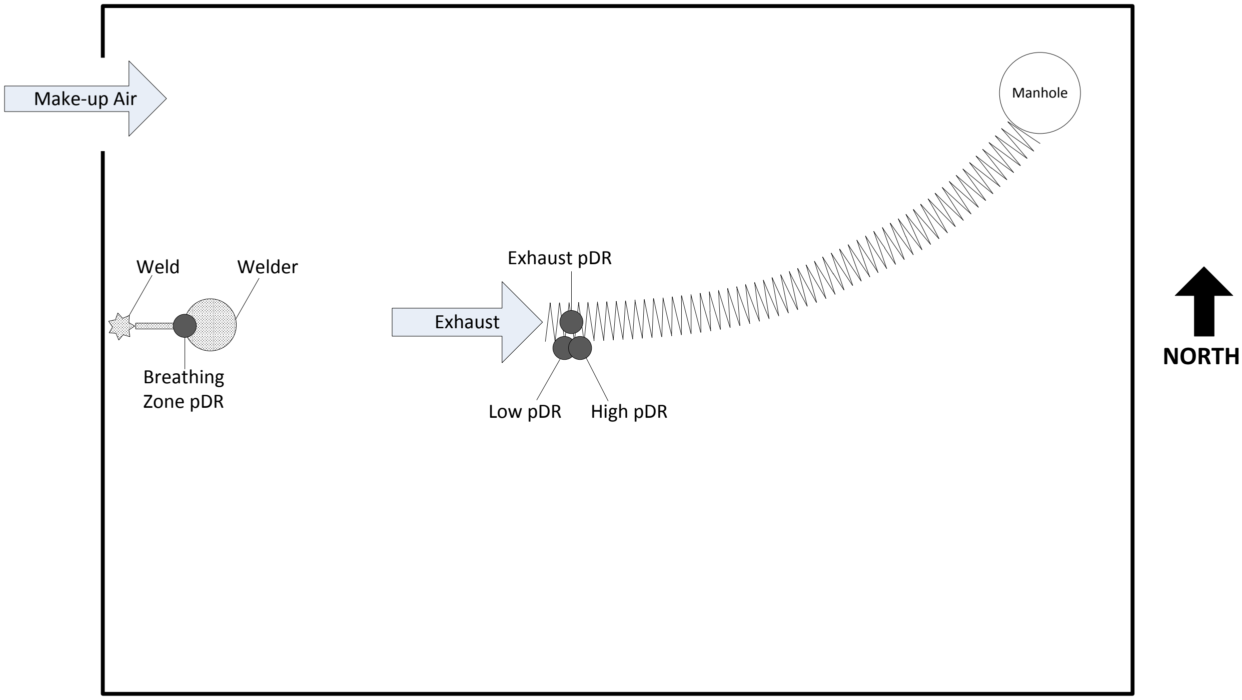
Aerial View

Scenario 1.3: Low Generation + GEV



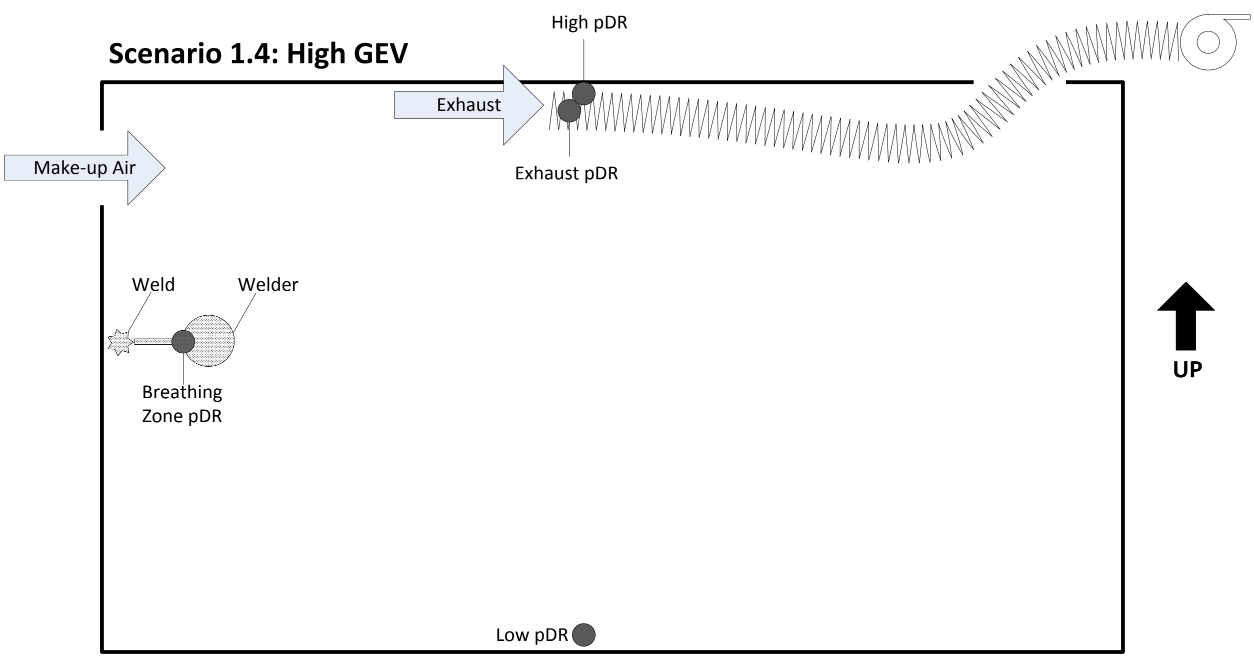
Lateral View

Scenario 1.4: High GEV



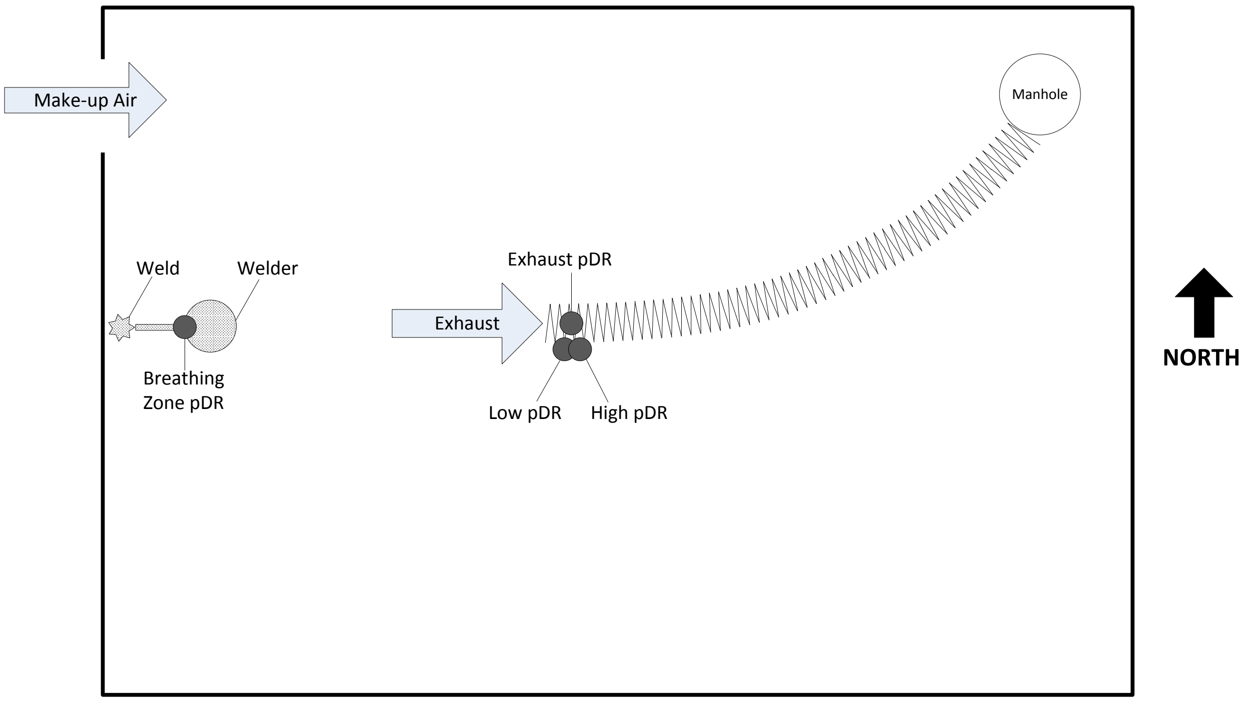
Aerial View

Scenario 1.4: High GEV



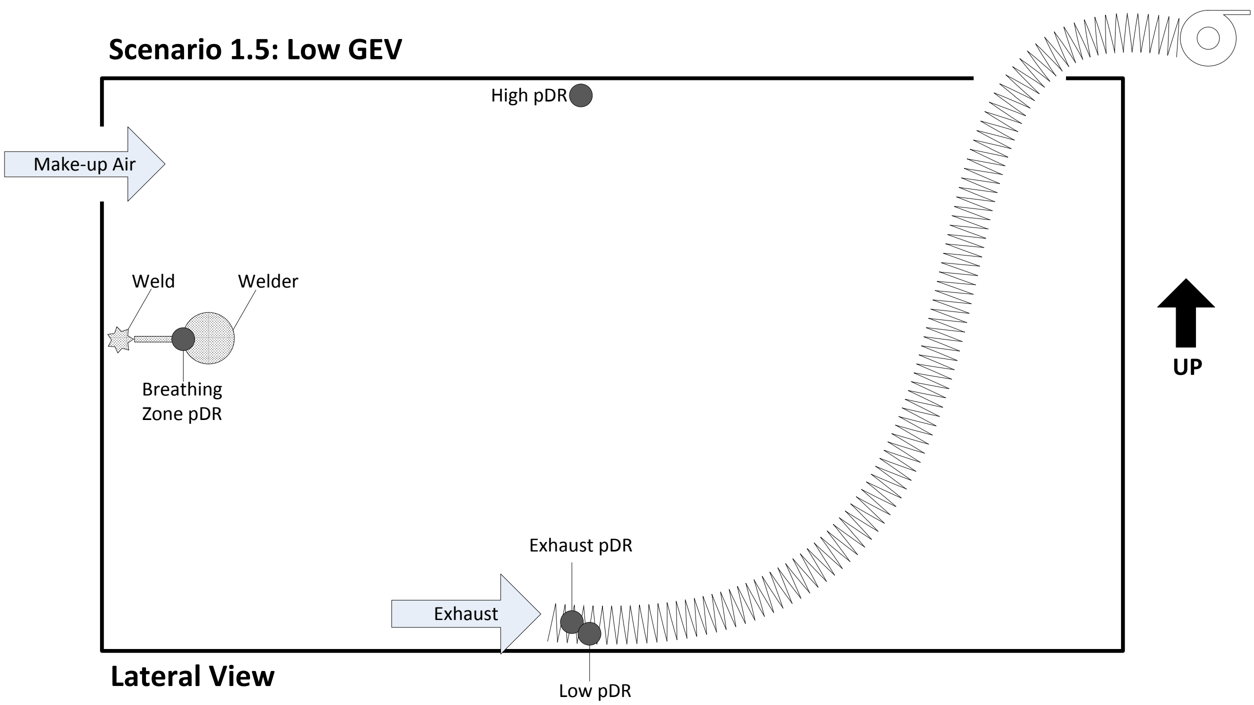
Lateral View

Scenario 1.5: Low GEV



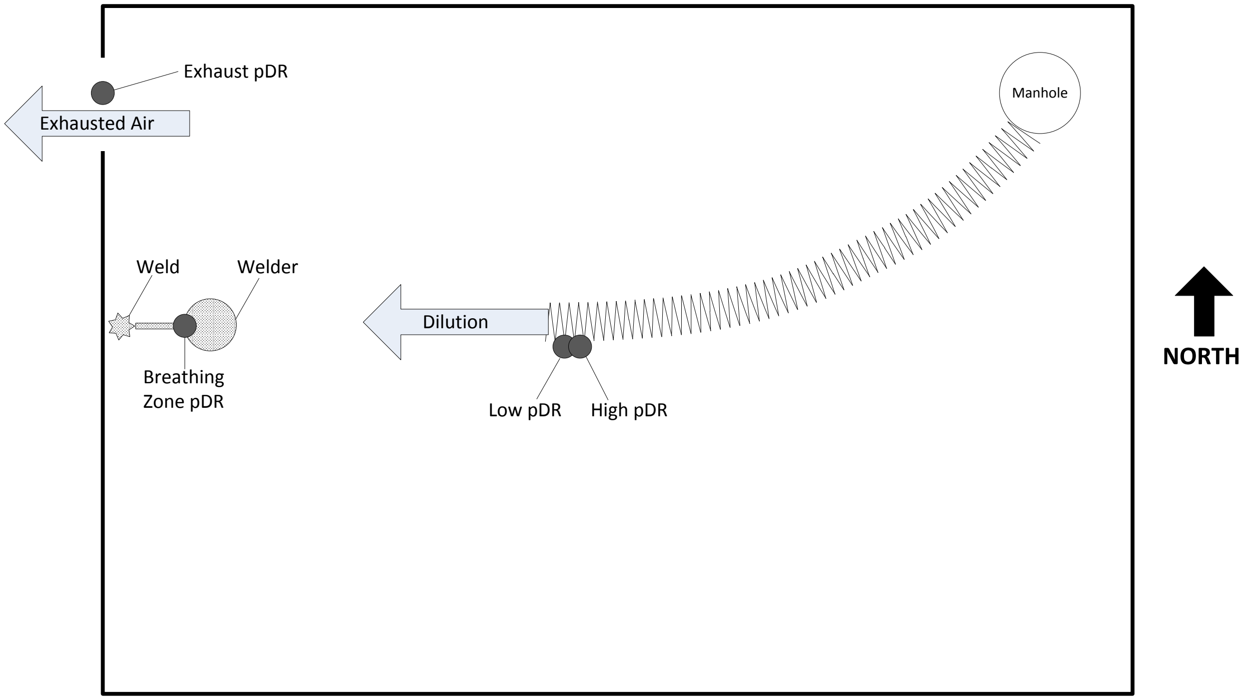
Aerial View

Scenario 1.5: Low GEV



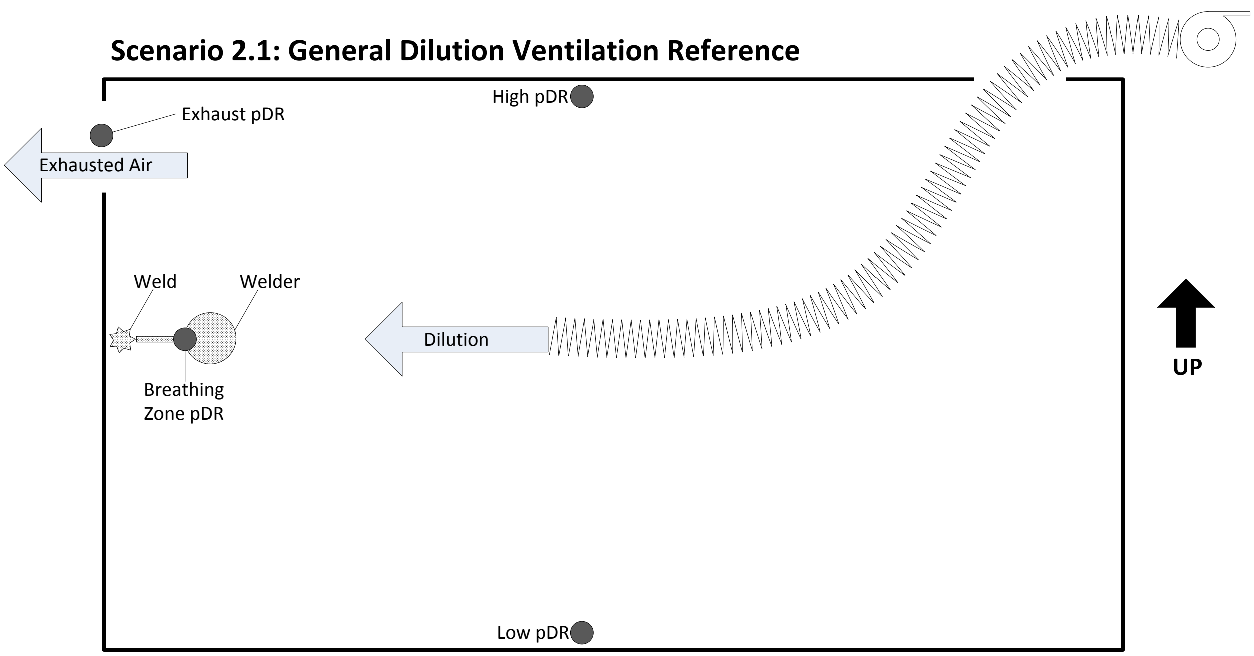
Lateral View

Scenario 2.1: General Dilution Ventilation Reference



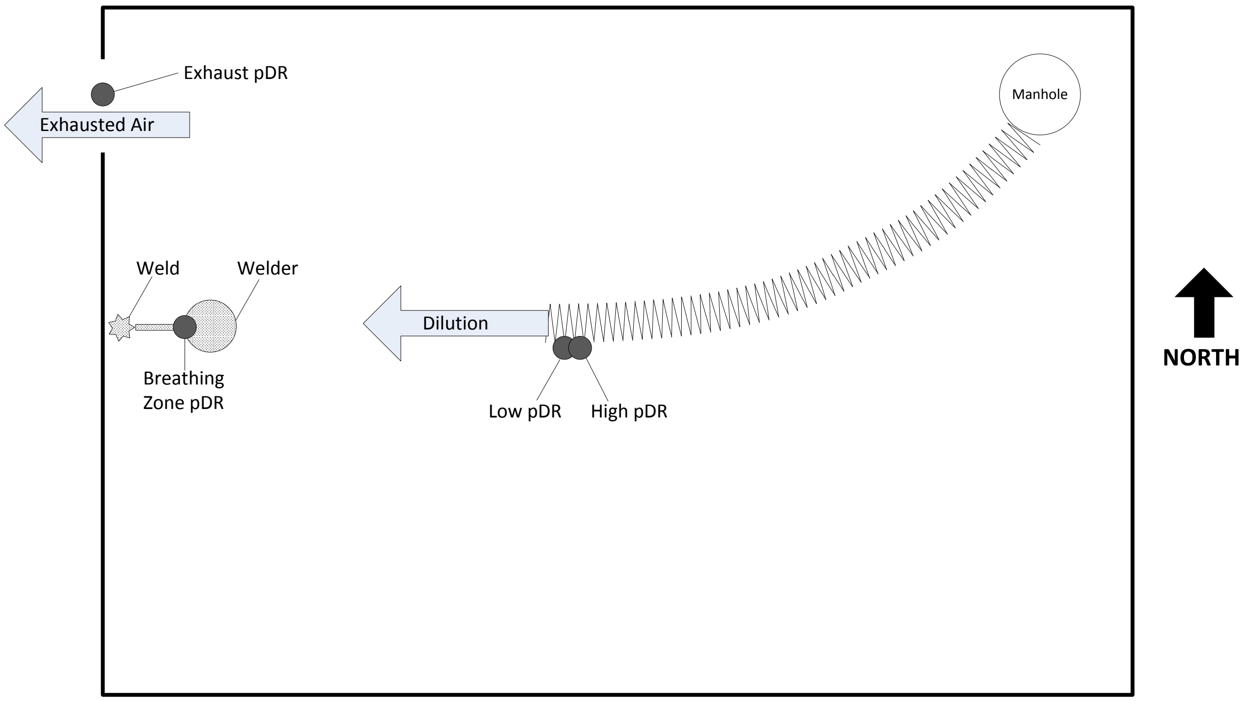
Aerial View

Scenario 2.1: General Dilution Ventilation Reference



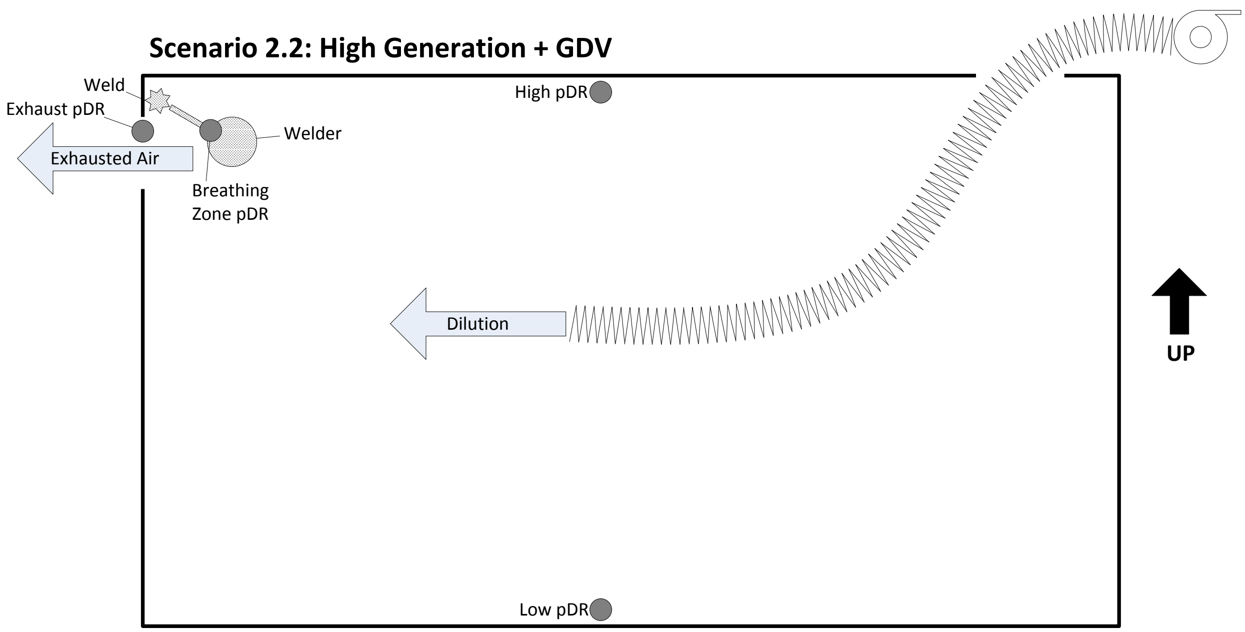
Lateral View

Scenario 2.2: High Generation + GDV



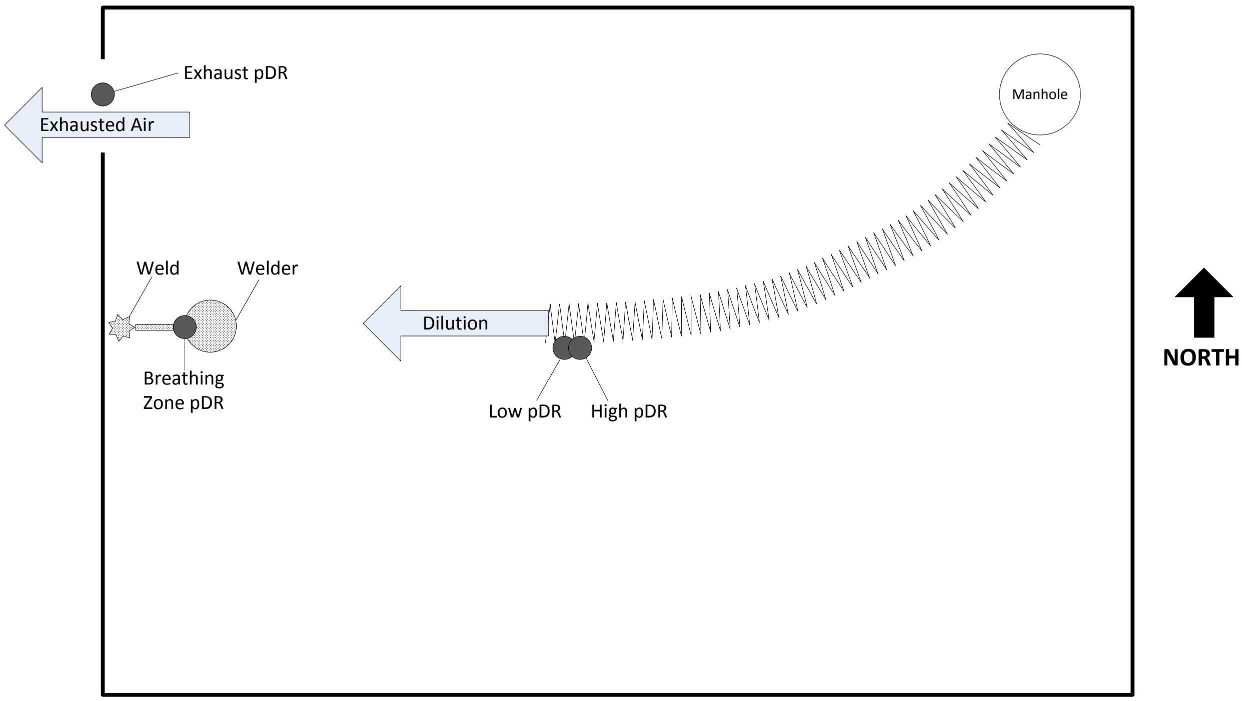
Aerial View

Scenario 2.2: High Generation + GDV



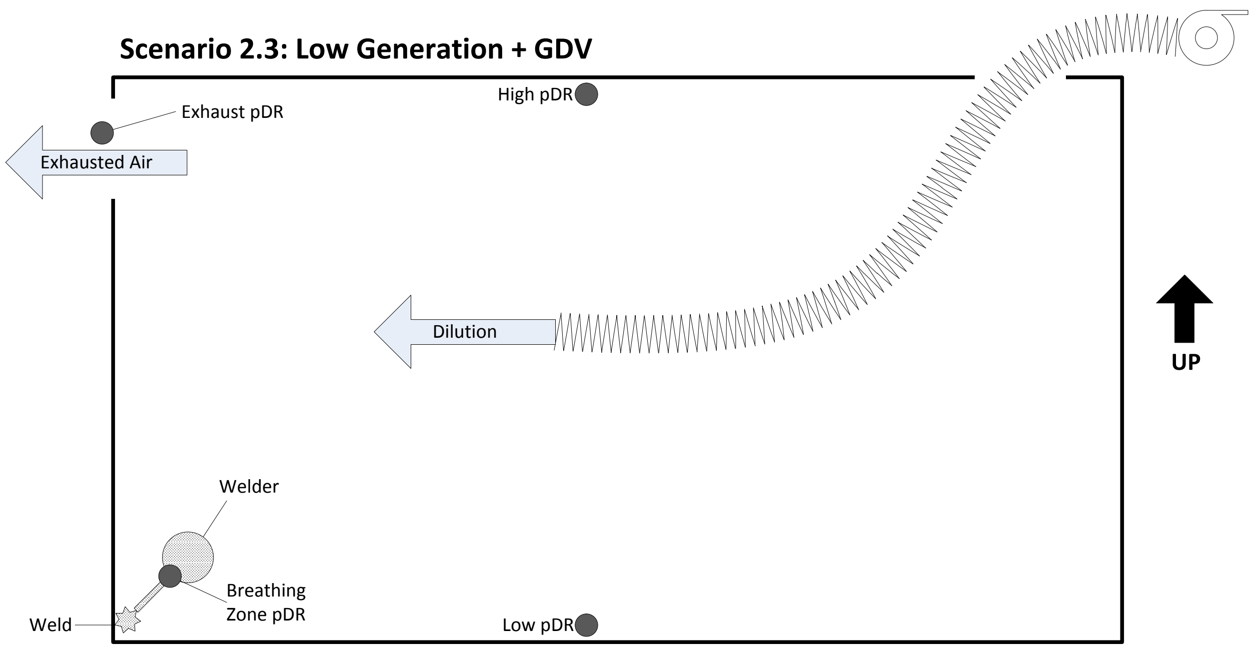
Lateral View

Scenario 2.3: Low Generation + General Dilution



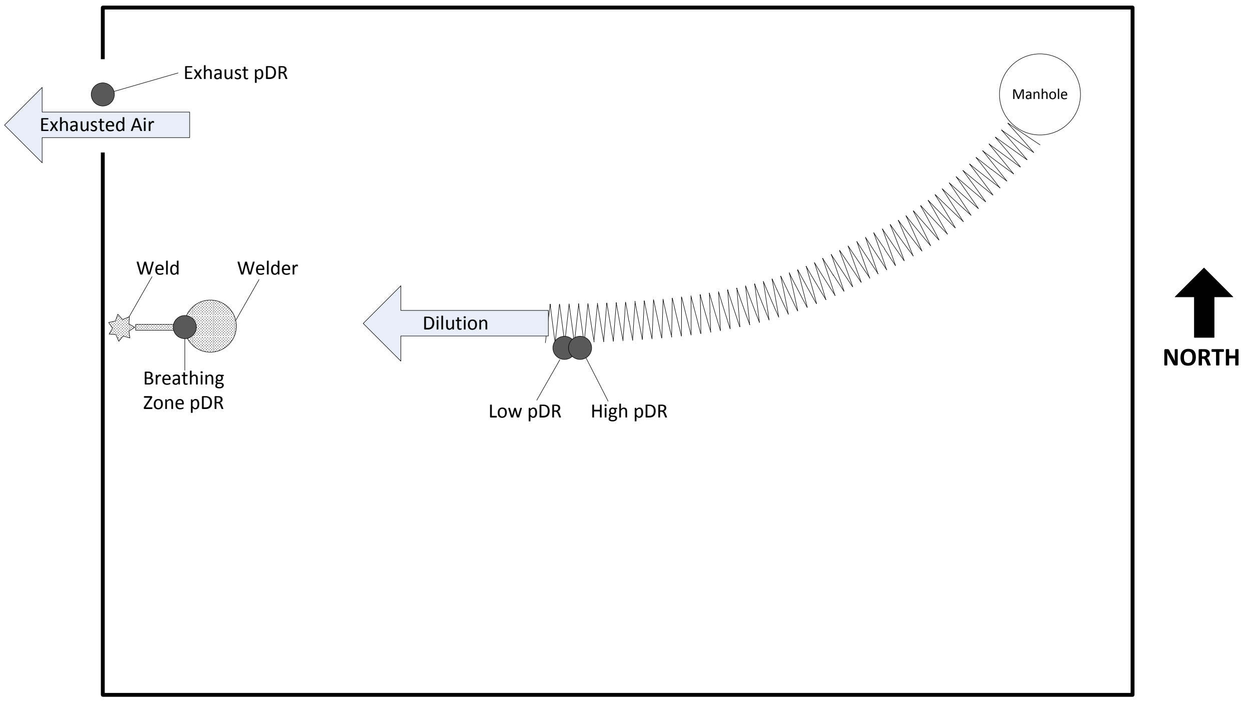
Aerial View

Scenario 2.3: Low Generation + GDV



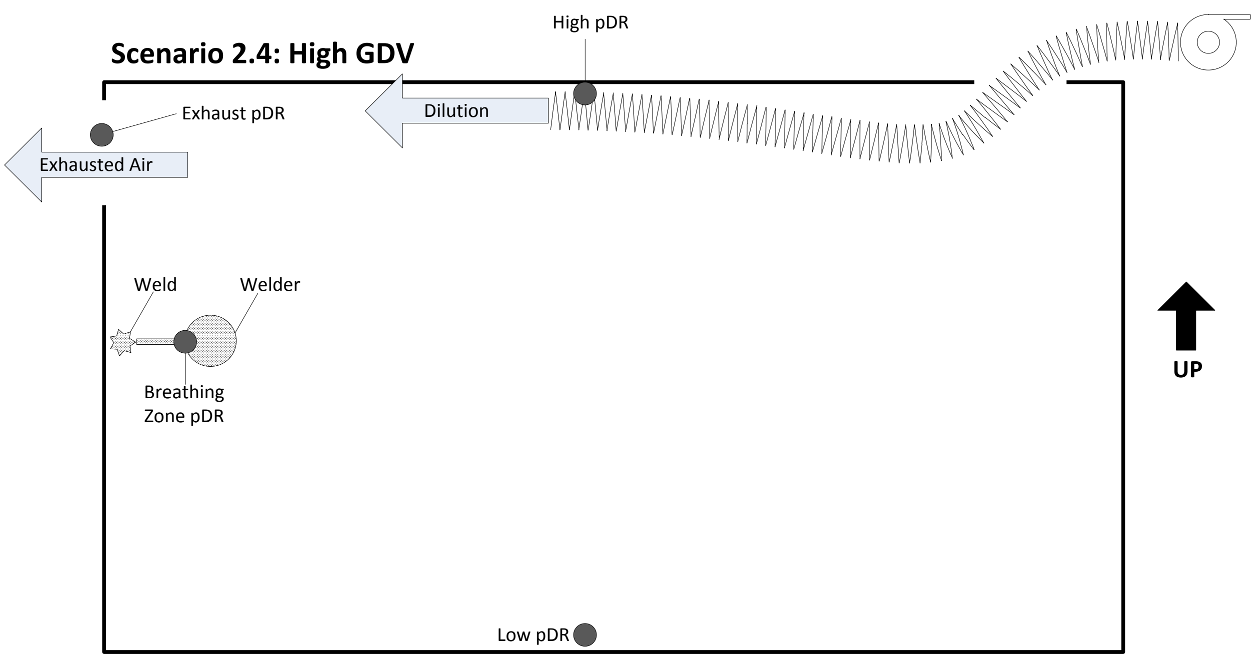
Lateral View

Scenario 2.4: High GDV



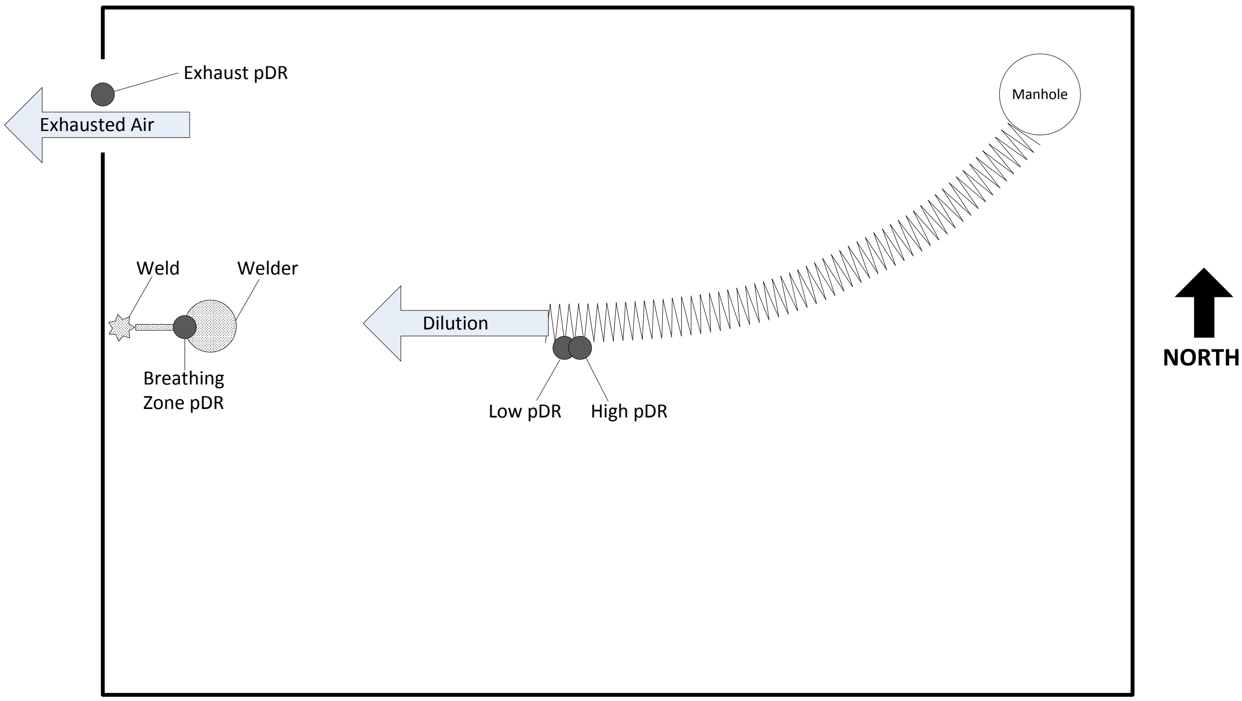
Aerial View

Scenario 2.4: High GDV



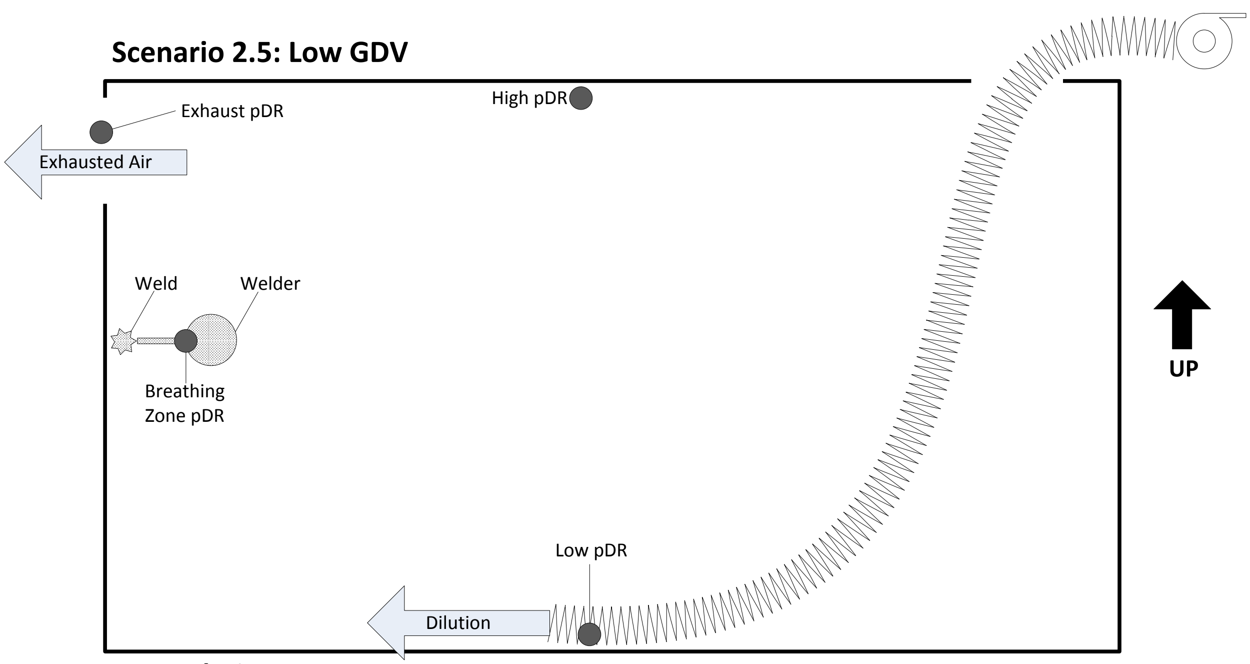
Lateral View

Scenario 2.5: Low GDV



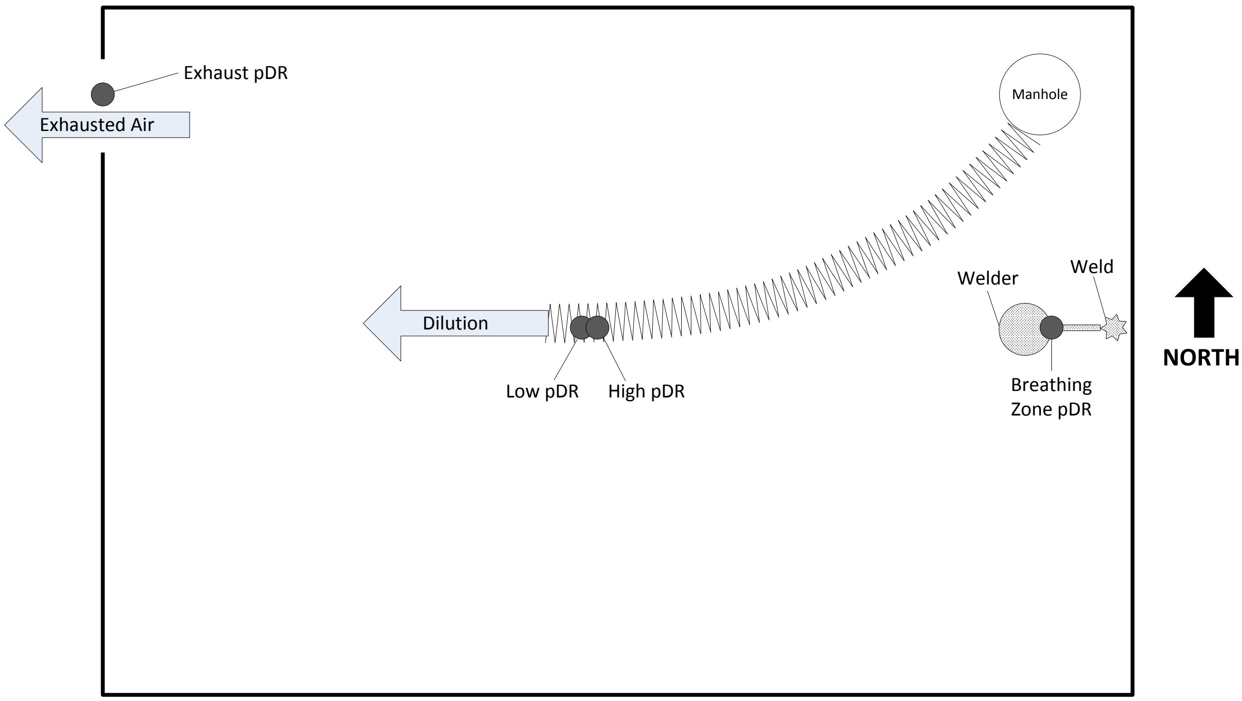
Aerial View

Scenario 2.5: Low GDV



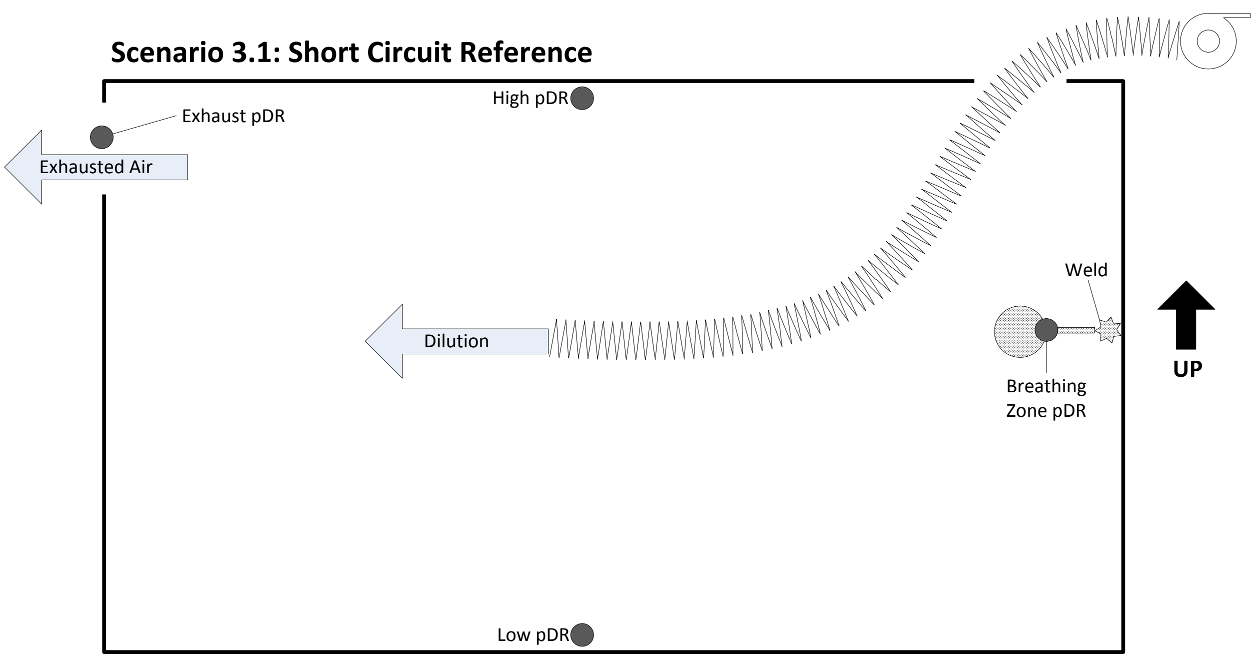
Lateral View

Scenario 3.1: Short Circuit Reference



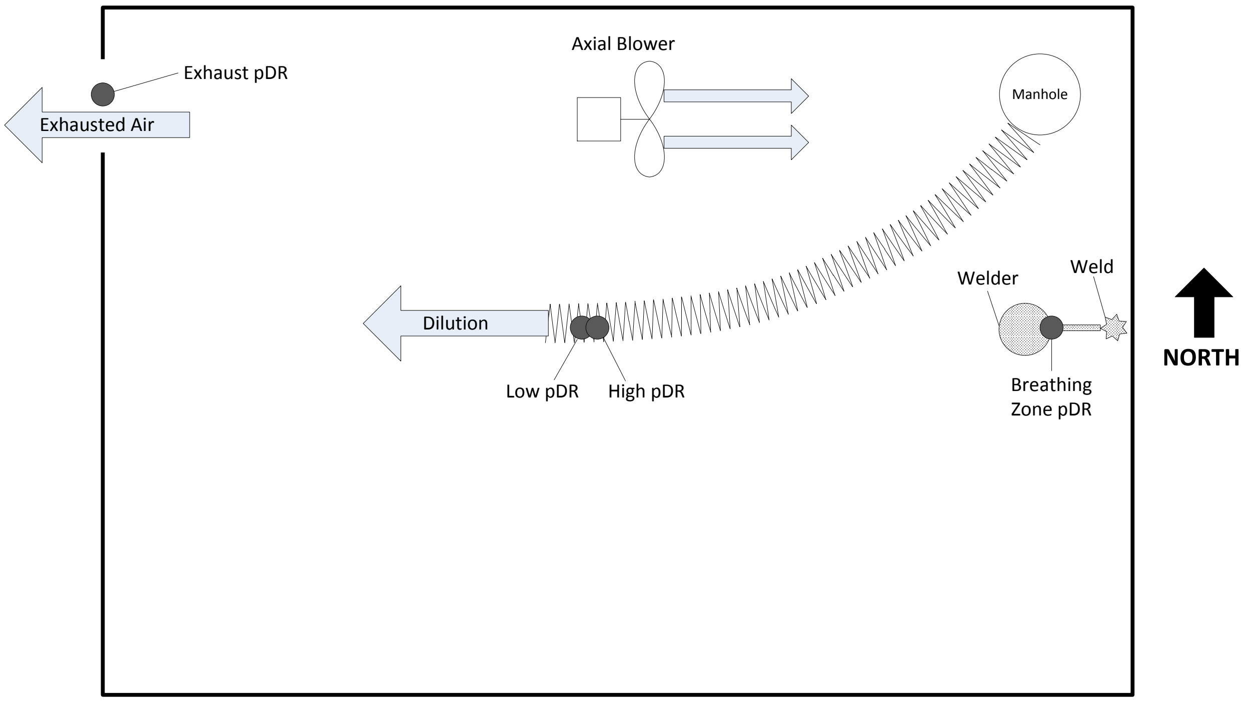
Aerial View

Scenario 3.1: Short Circuit Reference



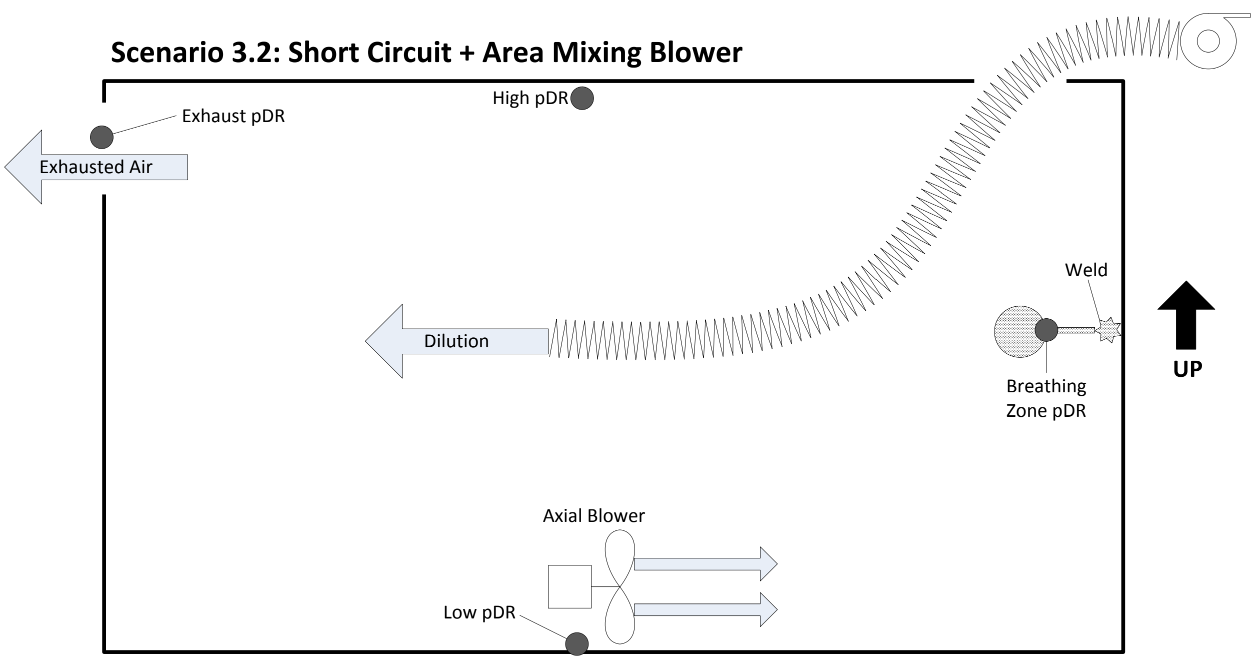
Lateral View

Scenario 3.2: Short Circuit + Area Mixing Blower



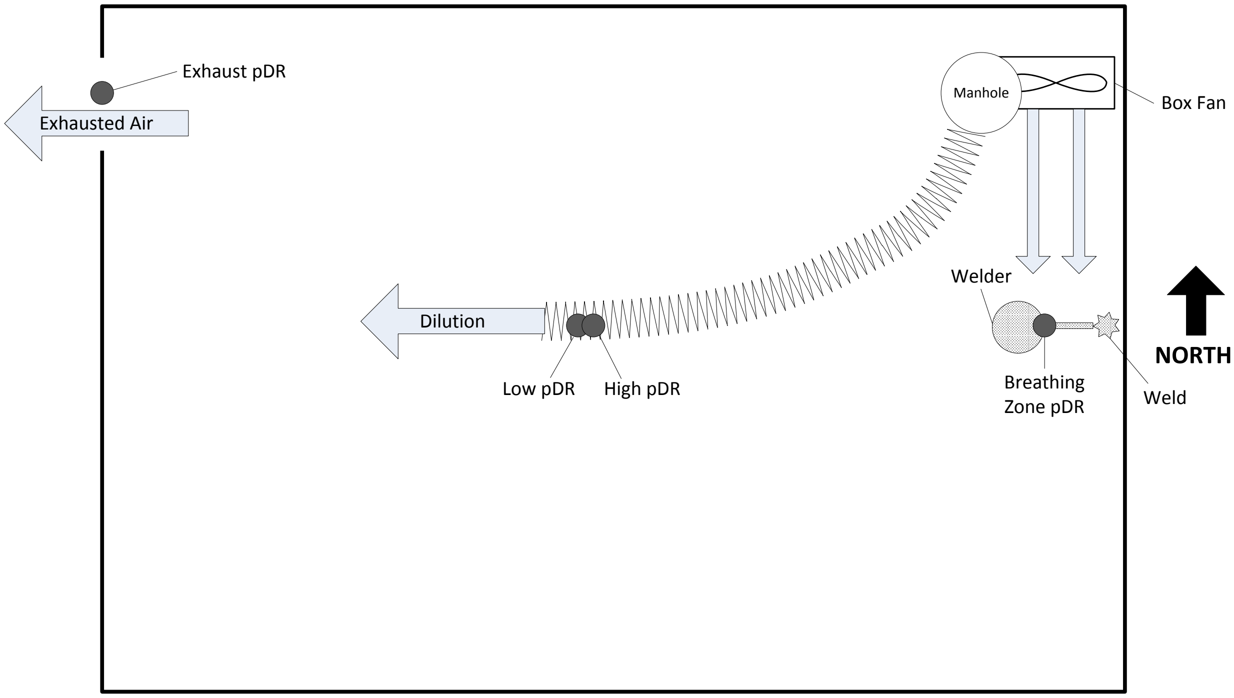
Aerial View

Scenario 3.2: Short Circuit + Area Mixing Blower



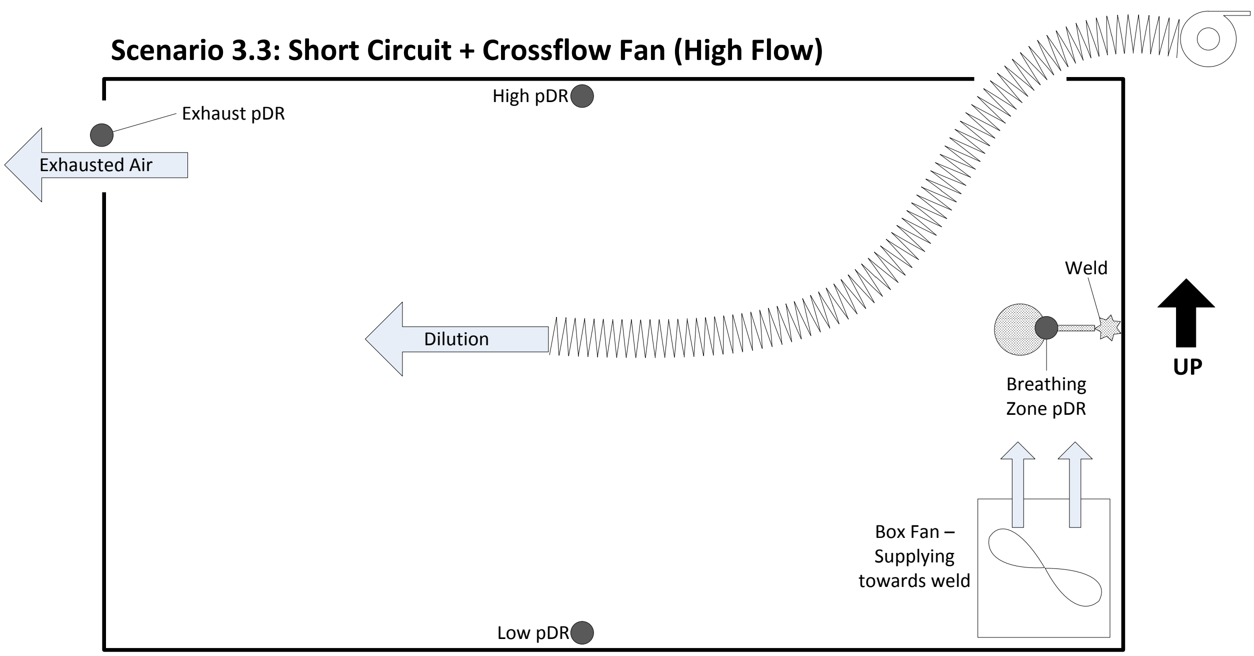
Lateral View

Scenario 3.3: Short Circuit + Crossflow Fan (High Flow)



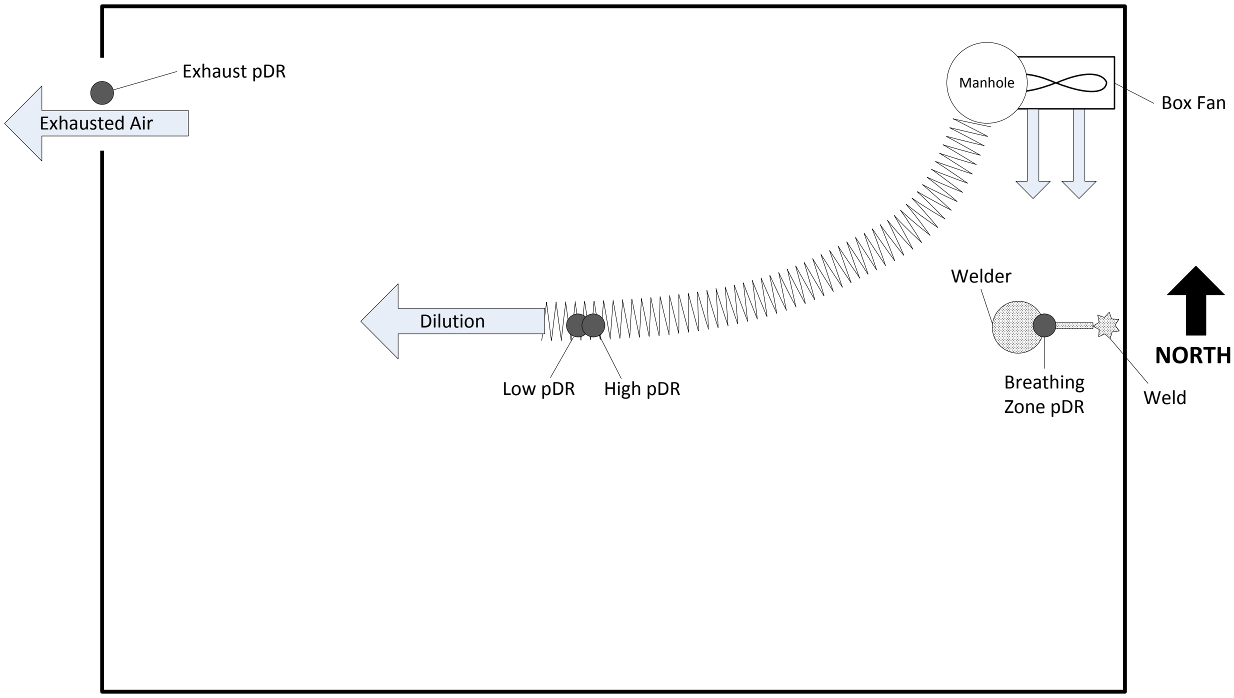
Aerial View

Scenario 3.3: Short Circuit + Crossflow Fan (High Flow)



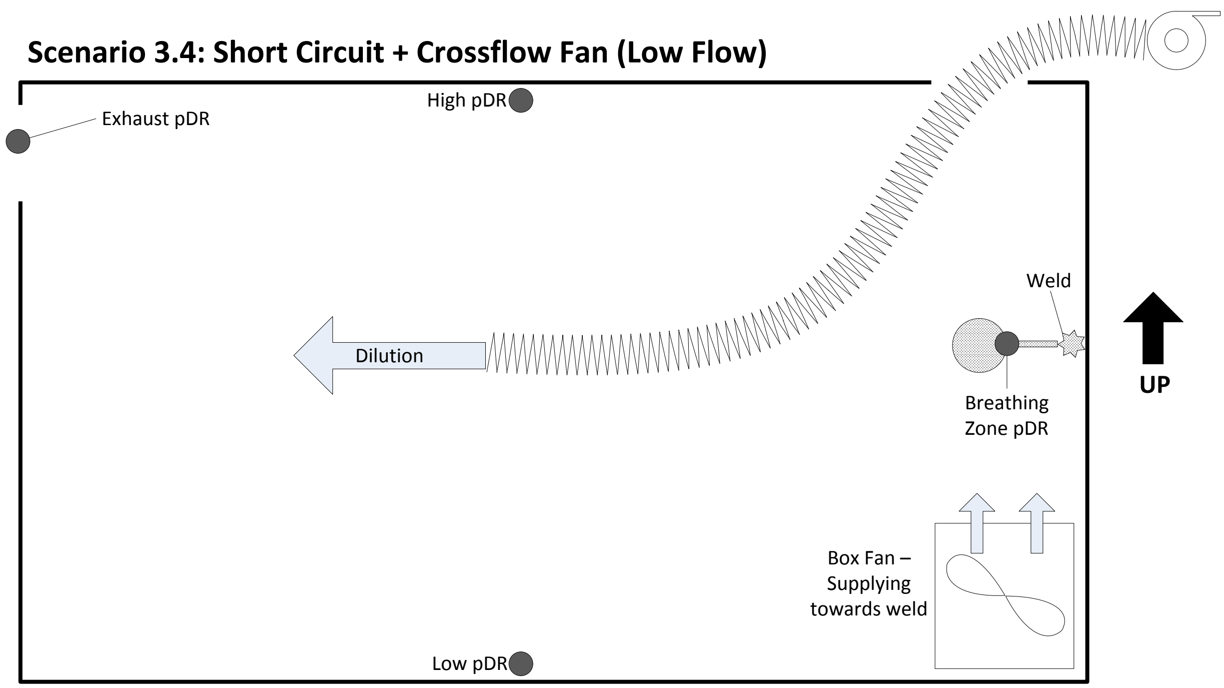
Lateral View

Scenario 3.4: Short Circuit + Crossflow Fan (Low Flow)



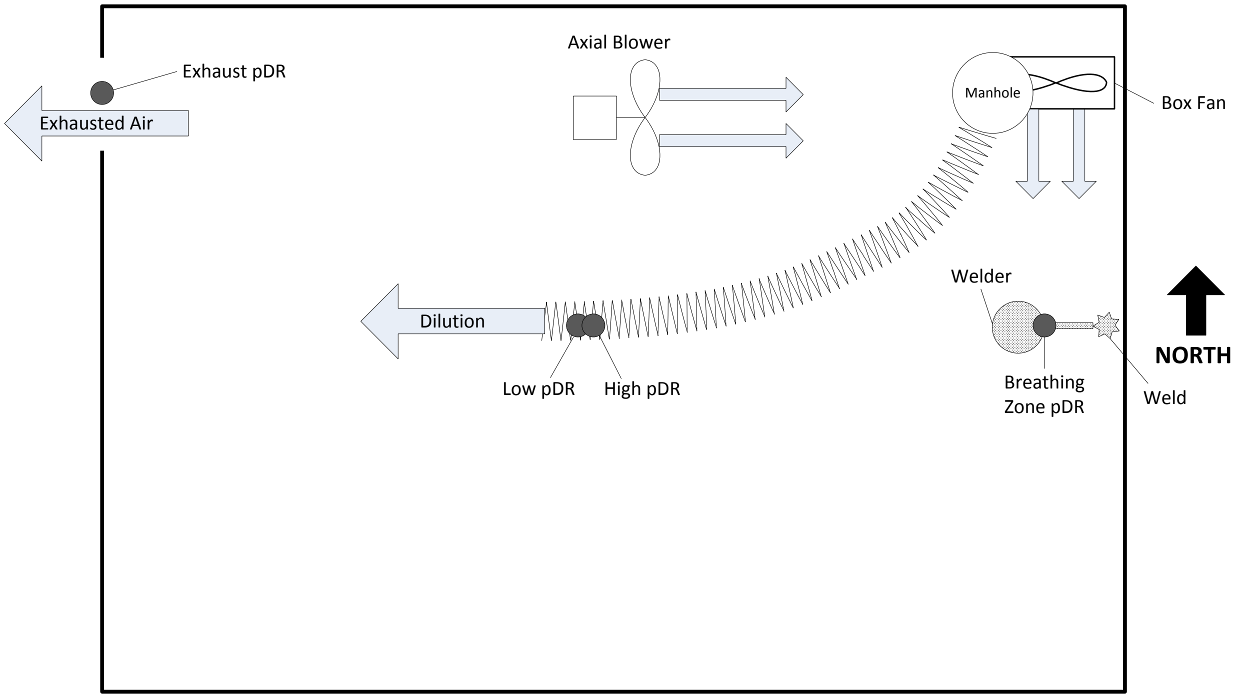
Aerial View

Scenario 3.4: Short Circuit + Crossflow Fan (Low Flow)



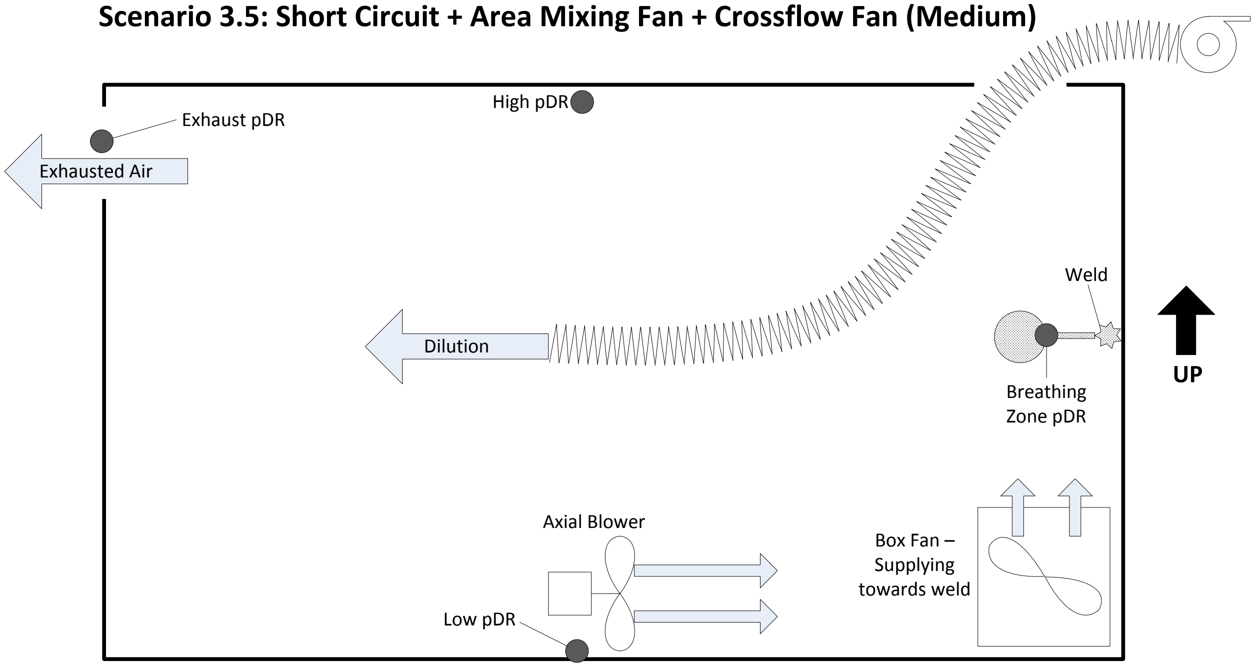
Lateral View

Scenario 3.5: Short Circuit + Area Mixing Fan + Crossflow Fan (Medium Flow)



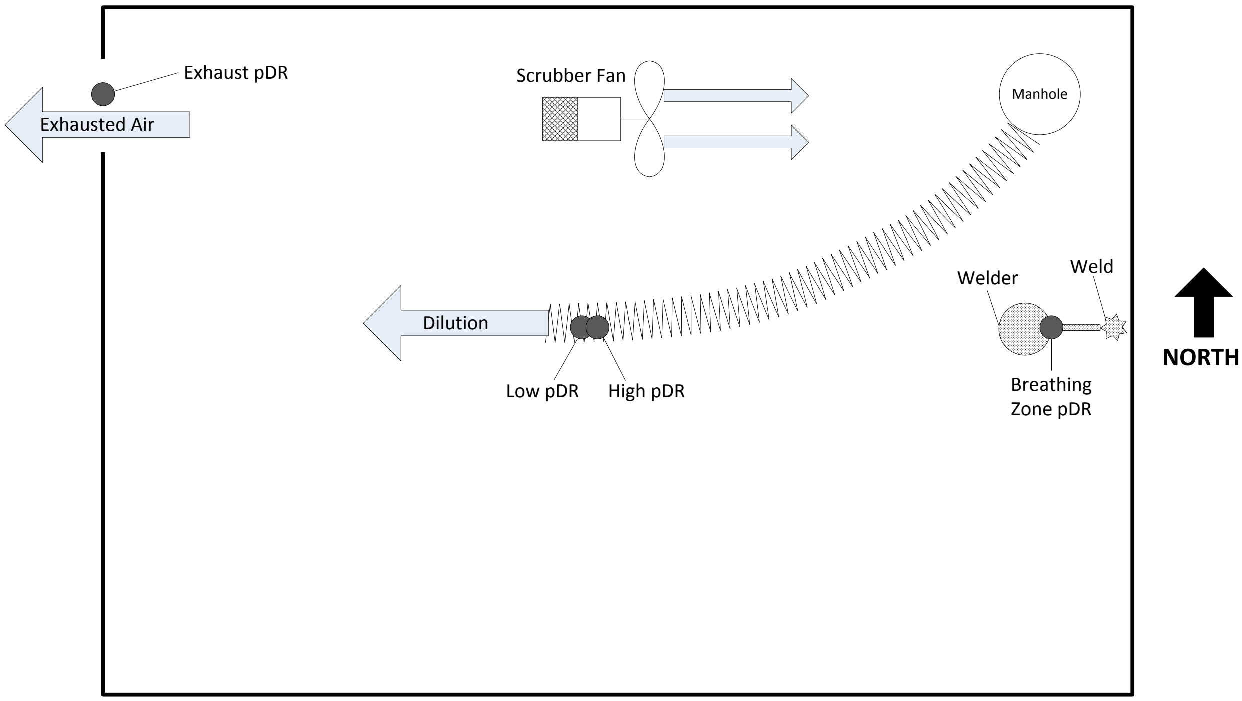
Aerial View

Scenario 3.5: Short Circuit + Area Mixing Fan + Crossflow Fan (Medium)



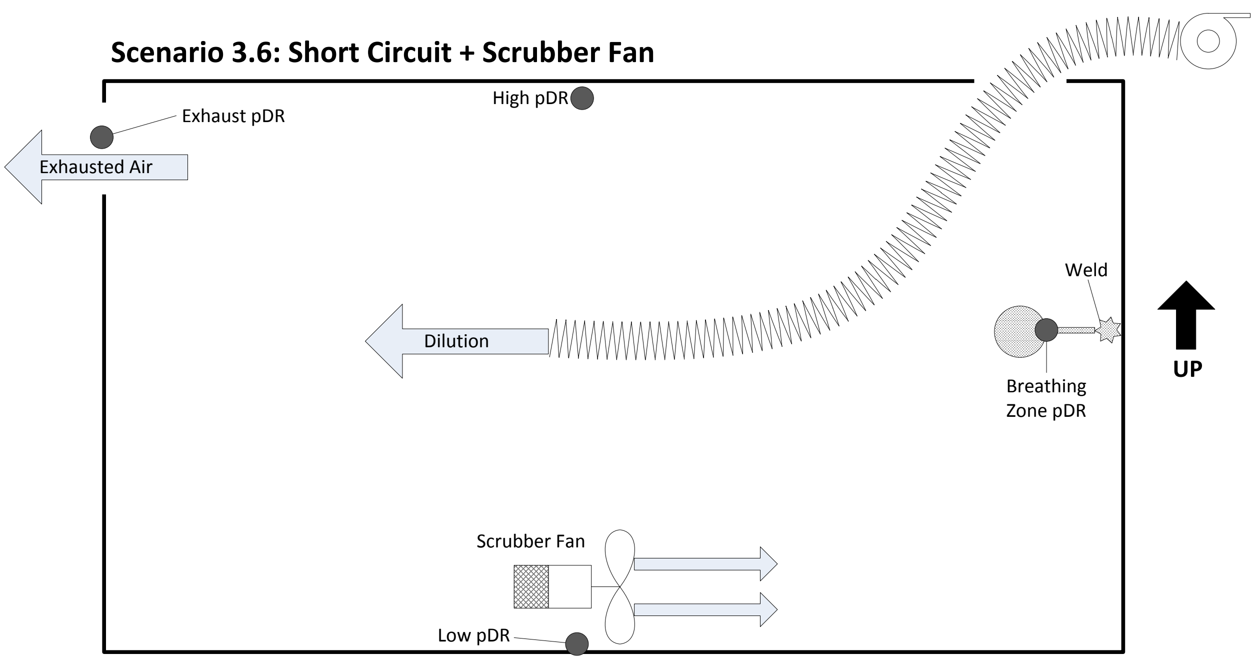
Lateral View

Scenario 3.6: Short Circuit + Scrubber Fan



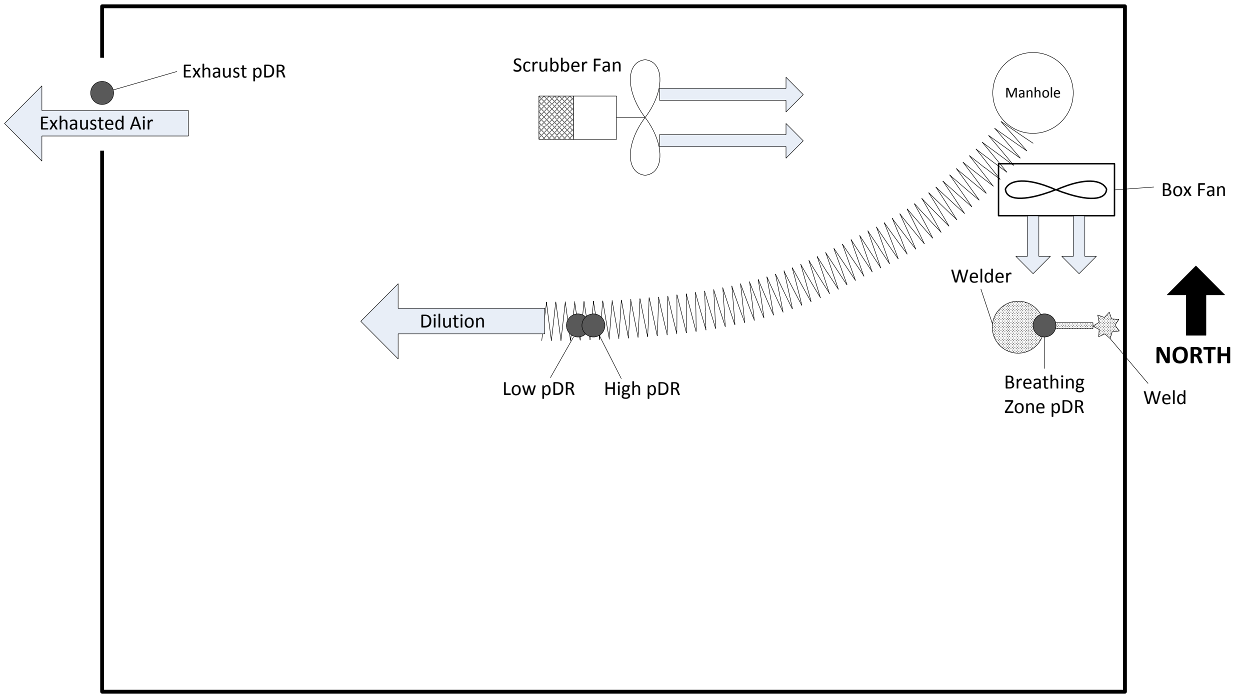
Aerial View

Scenario 3.6: Short Circuit + Scrubber Fan



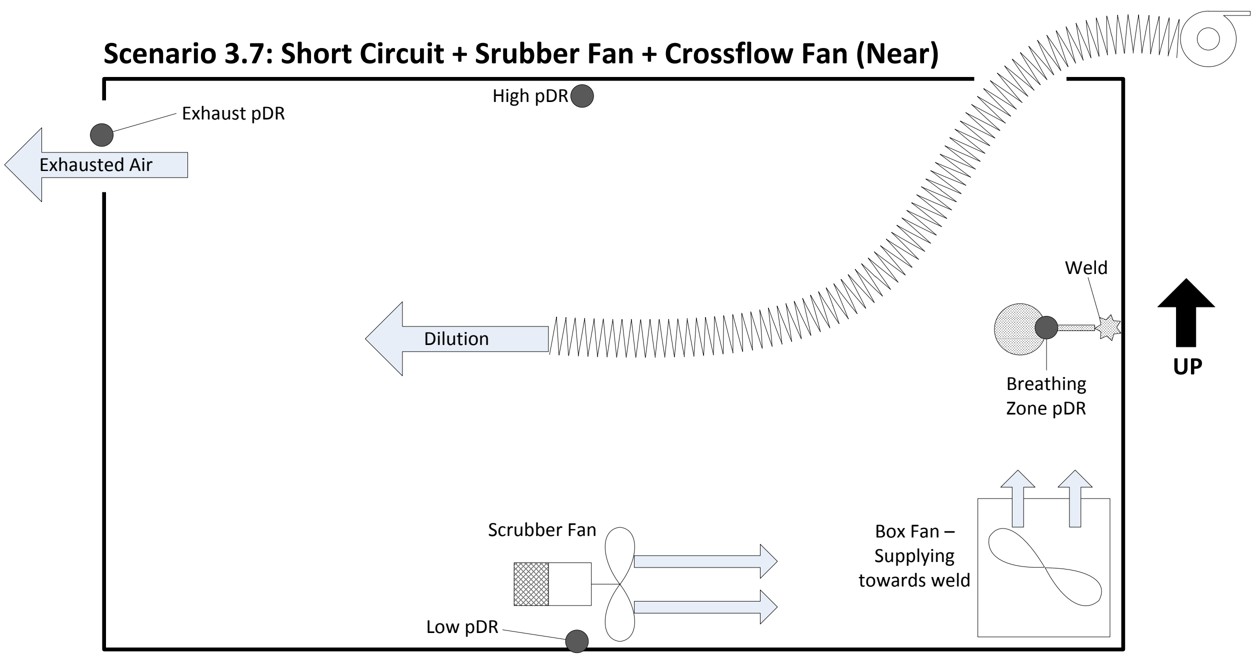
Lateral View

Scenario 3.7: Short Circuit + Srubber Fan + Crossflow Fan (Near)



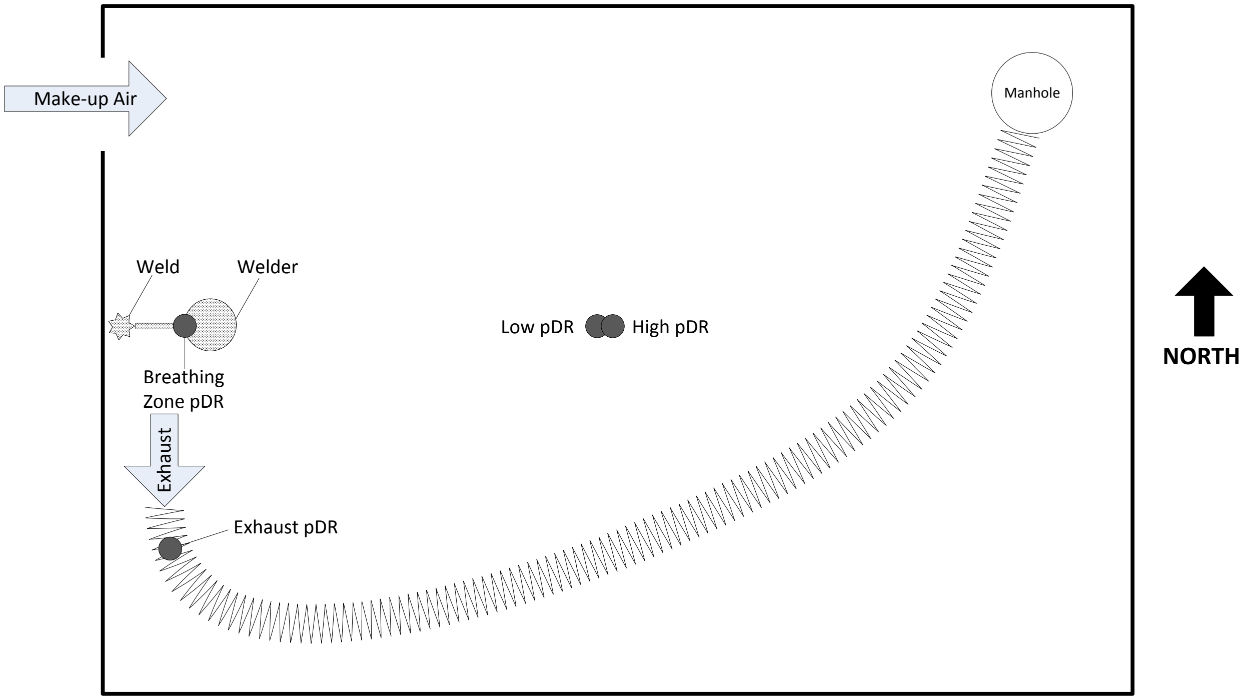
Aerial View

Scenario 3.7: Short Circuit + Srubber Fan + Crossflow Fan (Near)



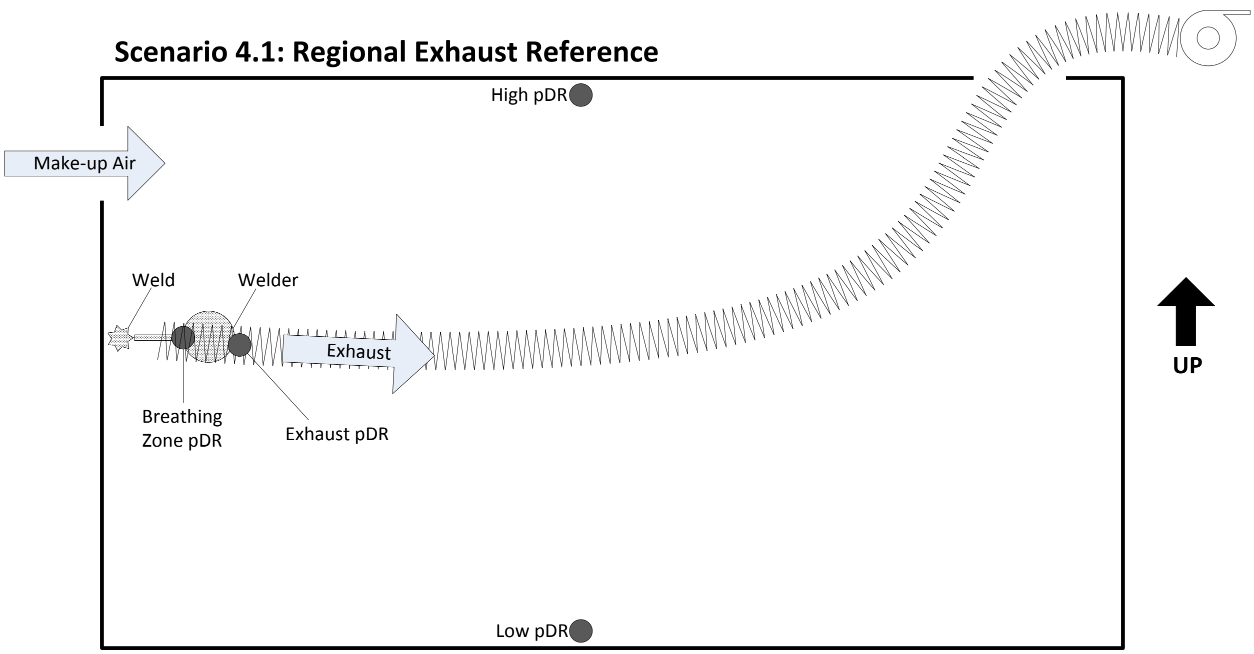
Lateral View

Scenario 4.1: Regional Exhaust Reference



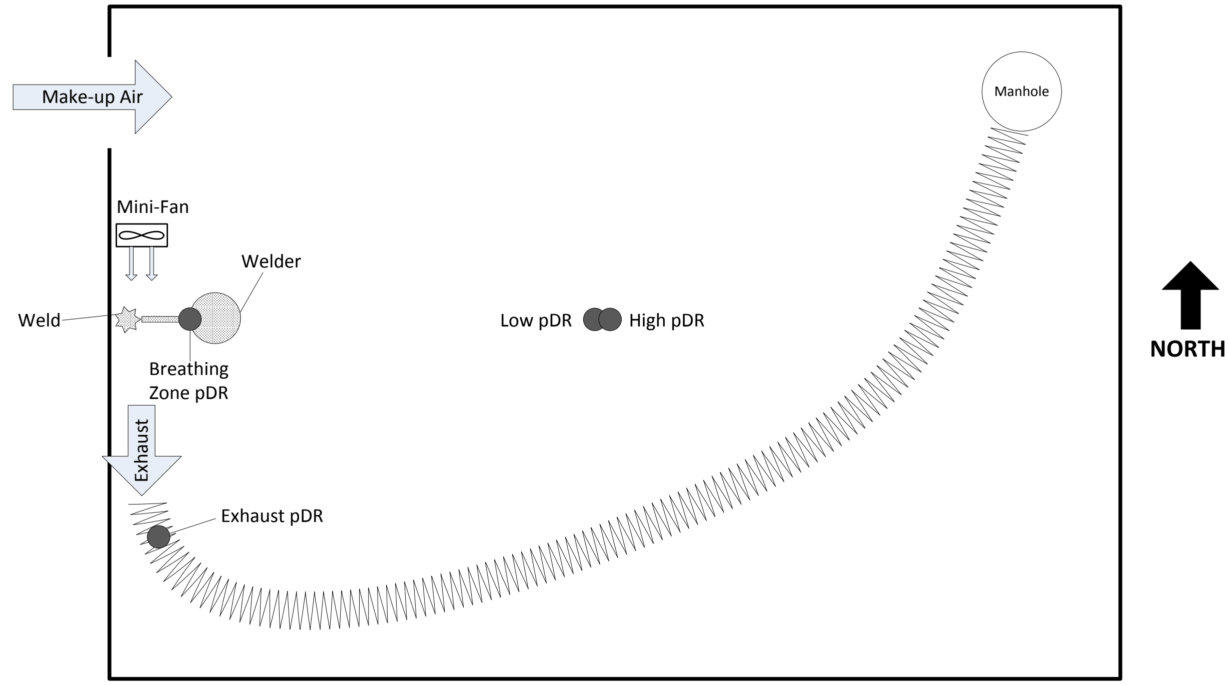
Aerial View

Scenario 4.1: Regional Exhaust Reference



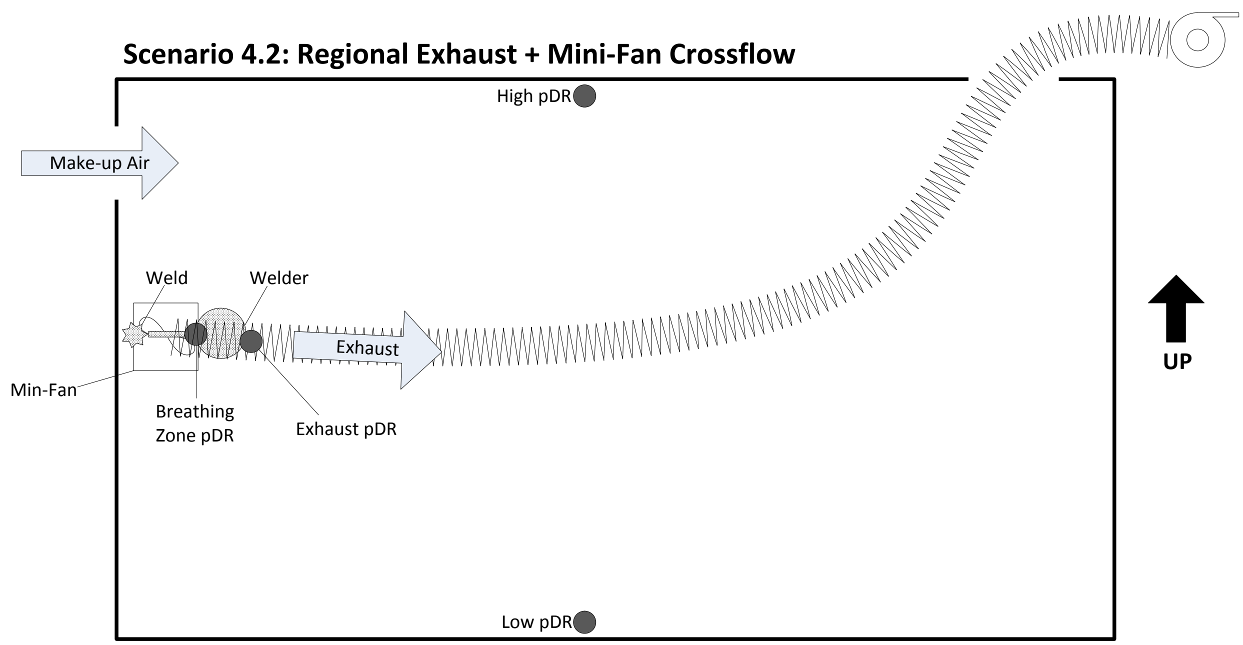
Lateral View

Scenario 4.2: Regional Exhaust + Mini-Fan Crossflow



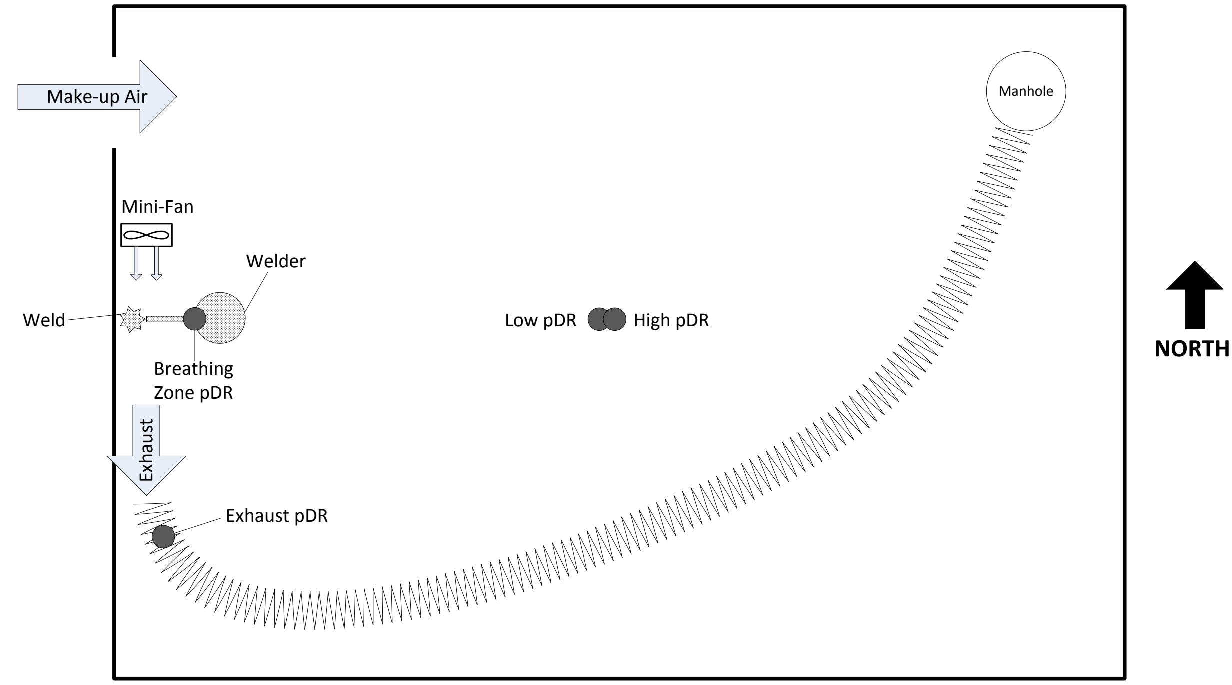
Aerial View

Scenario 4.2: Regional Exhaust + Mini-Fan Crossflow



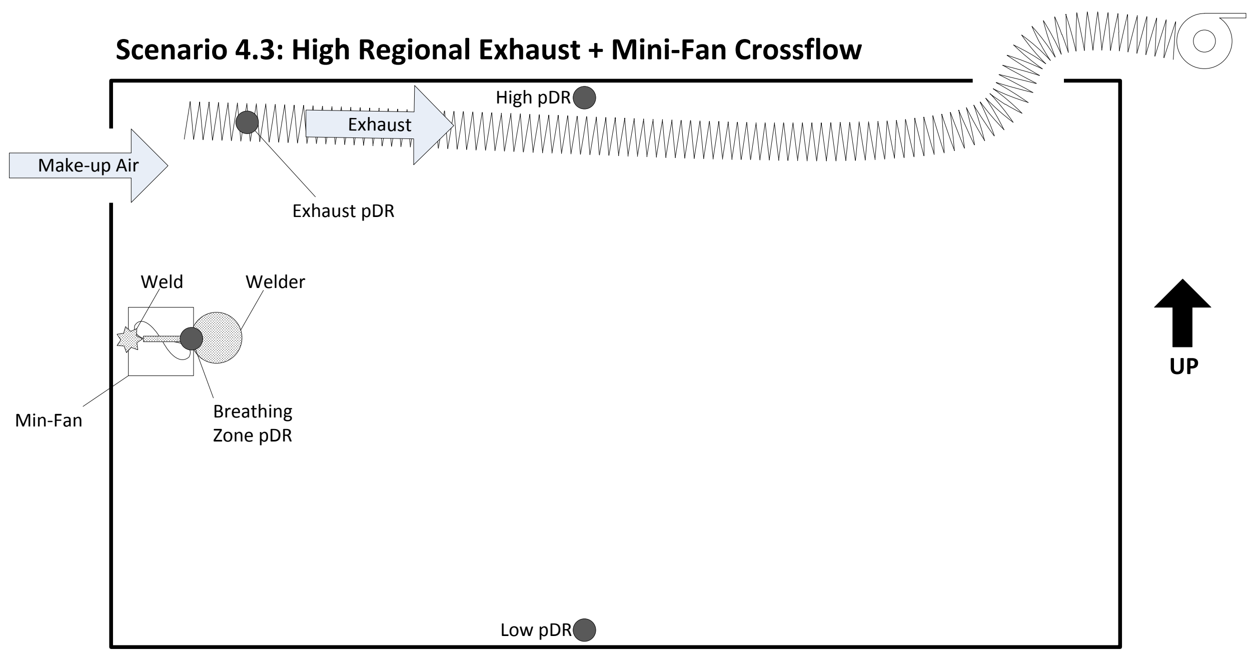
Lateral View

Scenario 4.3: High Regional Exhaust + Mini-Fan Crossflow



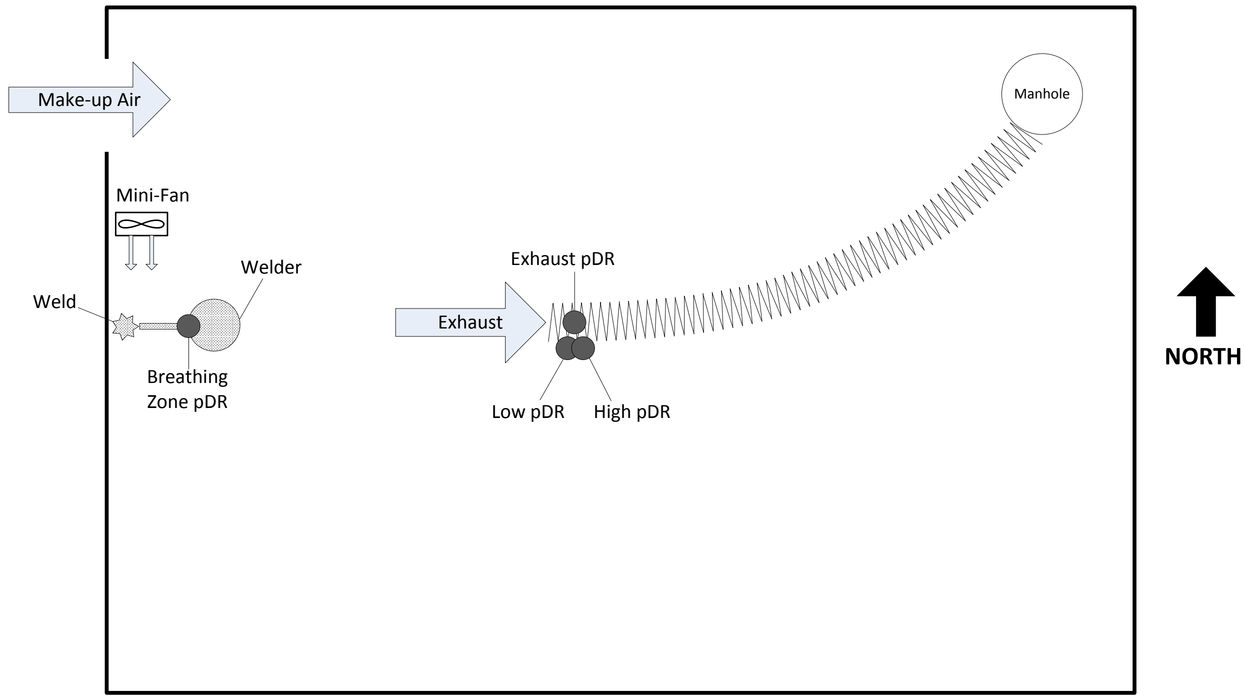
Aerial View

Scenario 4.3: High Regional Exhaust + Mini-Fan Crossflow



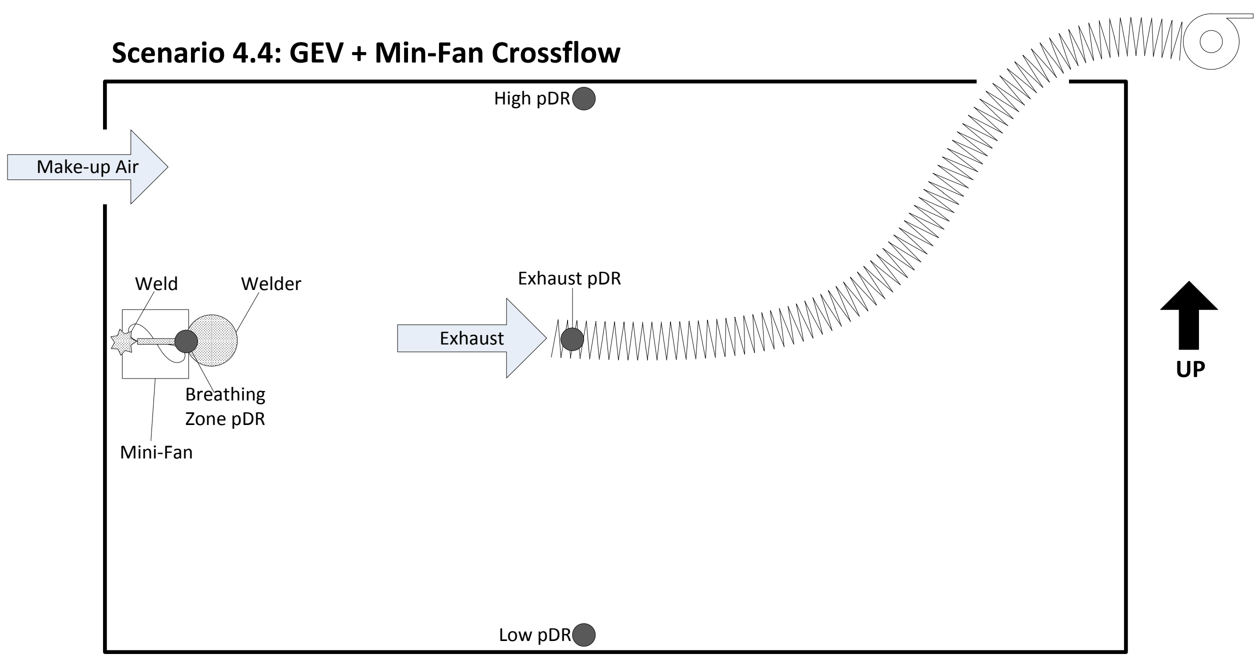
Lateral View

Scenario 4.4: GEV + Mini-Fan Crossflow



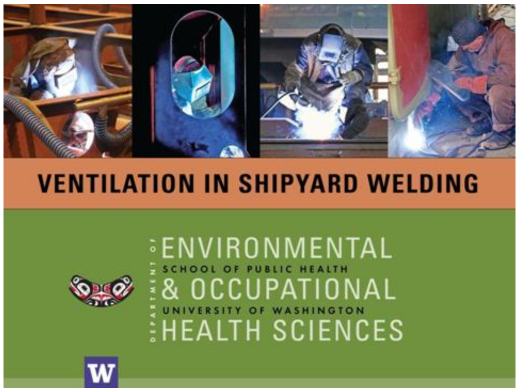
Aerial View

Scenario 4.4: GEV + Min-Fan Crossflow

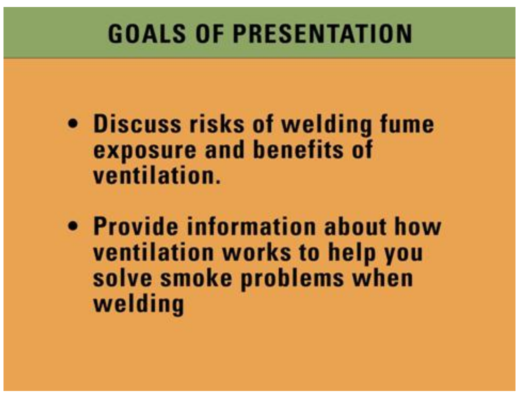


Lateral View

APPENDIX C: Intervention training



Slide 1



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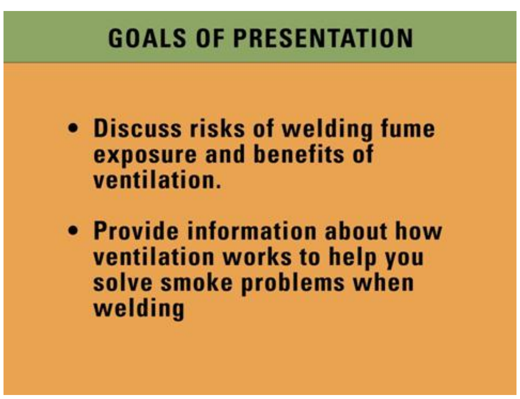

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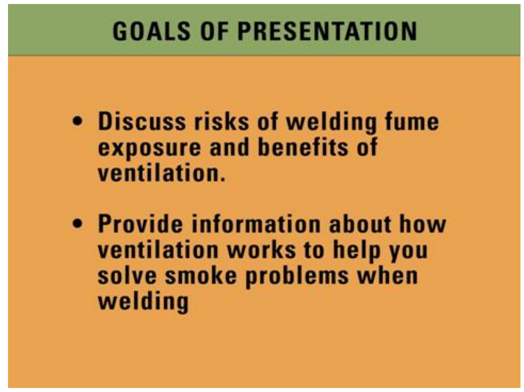
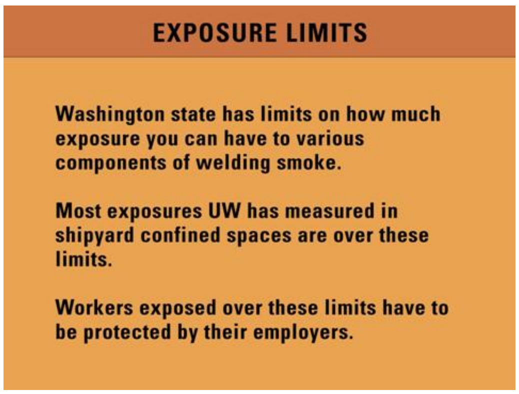


Slide 4

Slide 5

Slide 6

Slide 7



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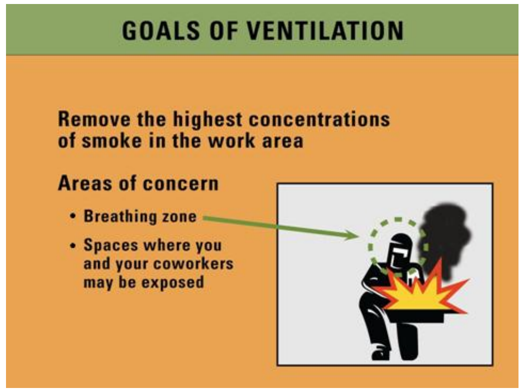

Slide 10

Slide 11

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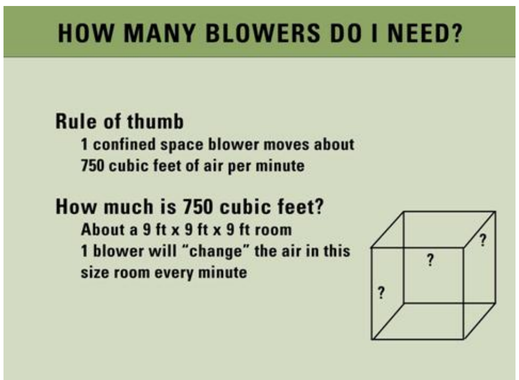
Slide 13



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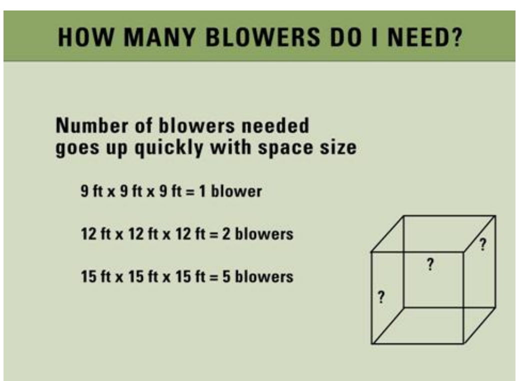

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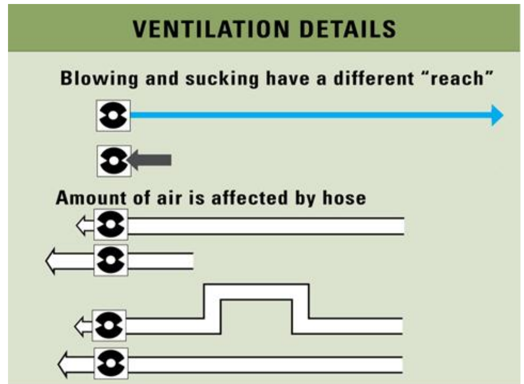
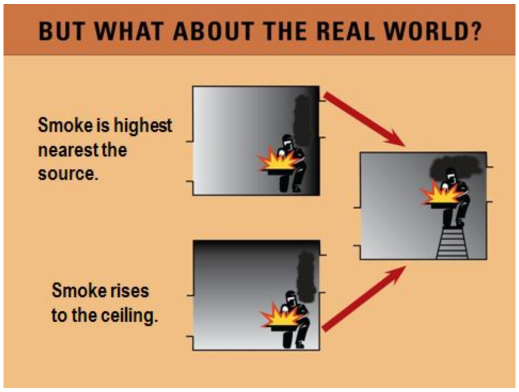


Slide 16

Slide 17

Slide 18



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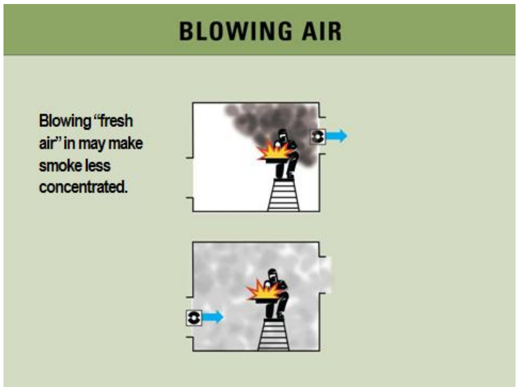

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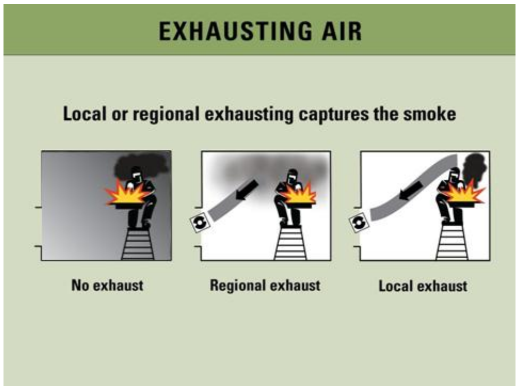

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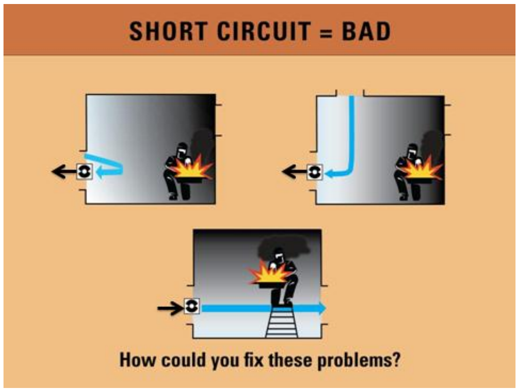

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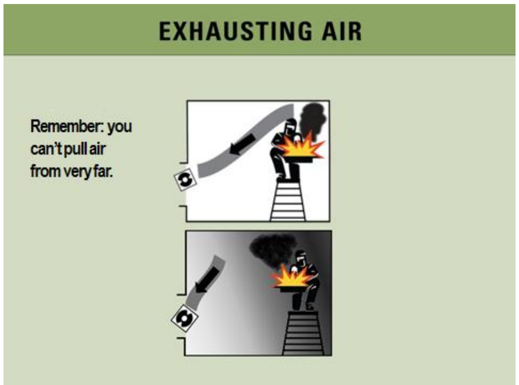

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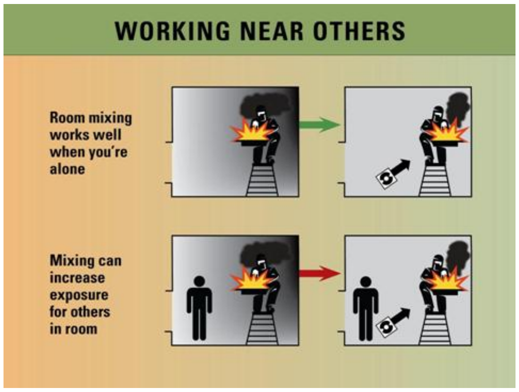

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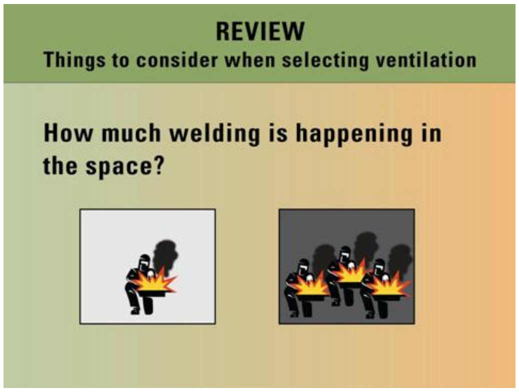

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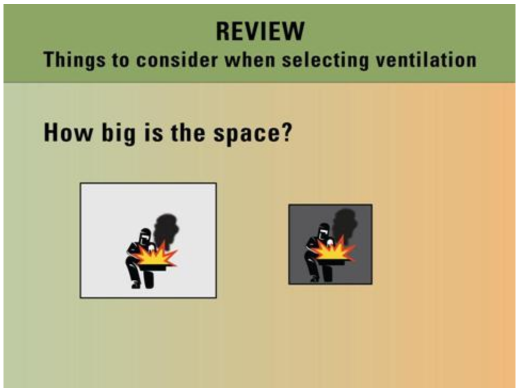

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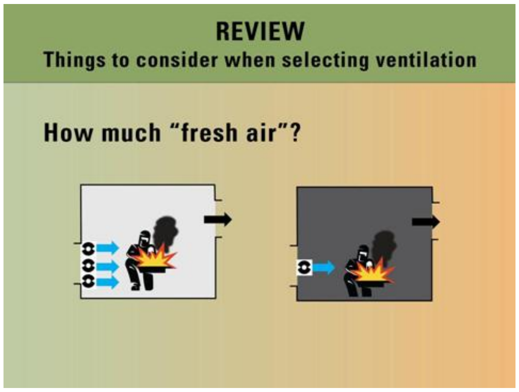
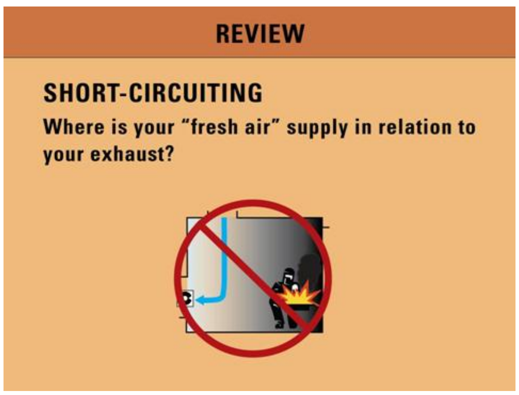


Slide 29

Slide 30

Slide 31



Slide 32

APPENDIX D: Observational tool

Researcher:	Start:	End:	Date:	Shipyard:

WORK

1. **Shape of space**
   ☐ Simple ☐ Complex
2. **Work area enclosed by shed, dry dock, tent, etc.**
   ☐ Yes ☐ No
3. **Type of job**
   ☐ New Construction ☐ Repair
4. **Type of space**
   ☐ Outside ***If Outside → Skip to6***
   ☐ Exterior of vessel
   ☐ Partially enclosed space
   ☐ Enclosed space
   ☐ Confined 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 (FCAW)	☐ Oxyacetylene
☐Not Sure	☐Other __________	

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