THESIS

# COMPARISON OF HEXAVALENT CHROMIUM AND WELDING FUMES INSIDE AND OUTSIDE OF THE WELDING HELMET

Submitted by

Karen Diaz-Rivera

Department of Environmental and Radiological Health Sciences

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Master's Committee:

Advisor: William Brazile

Stephen Reynolds
Jeffrey Collett

# ABSTRACT

## COMPARISON OF HEXAVALENT CHROMIUM AND WELDING FUMES INSIDE AND OUTSIDE OF THE WELDING HELMET

The primary objective of this study was to determine if welding fumes and specific metal concentrations were significantly different between samples taken inside and outside of the welding helmet to determine the most appropriate location of the personal sampling device and best estimate exposure.

Personal air samples were collected simultaneously inside and outside of the welding helmet for concentration comparison of welding fumes ($n = 12$) and hexavalent chromium ($n = 15$) during stainless steel tungsten inert gas welding tasks. A total of fifteen welders were sampled in a manufacturing setting and a brewery for a total of 27 inside and outside paired samples.

A statistically significance difference ($p = 0.05$) between inside and outside welding helmet concentrations was found for total welding fumes, iron, total chromium, and nickel using a Wilcoxon paired test, where most of the inside-helmet concentrations were lower. Hexavalent chromium and manganese concentrations were not significantly different when comparing inside and outside welding helmet concentrations. A correlation among welding fumes, iron, nickel, and total chromium concentrations was observed utilizing Spearman's rank-order correlation. The mean for hexavalent chromium concentrations difference was 11 $\mu g/m^3$, when the outlier was included in the analysis and 0.07 $\mu g/m^3$ without the outlier. The median concentrations difference was 0.06 $\mu g/m^3$ with or without the outlier in the analysis. The 95% confidence interval for hexavalent chromium inside concentration was 0.1 $\mu g/m^3$ to 0.34 $\mu g/m^3$ and 0.13

$\mu g/m^3$ to 0.4 $\mu g/m^3$ for outside of the welding helmet concentration. One sample set for hexavalent chromium exceeded the permissible exposure limit (PEL), recommended exposure limit (REL), and threshold limit value (TLV).

Based on the results, a high variation of concentrations was found between the inside and outside of the welding helmet concentrations depending on the metal fume analyzed. Manganese had the lowest metal content in the stainless steel welding rods as well as the sampled welding fumes. The greatest variation in concentration ratios was observed for manganese and hexavalent chromium when comparing inside and outside concentrations. These two factors, lower metal contribution in welding rods and variation in concentrations can be speculated to affect the statistical non significant difference found for manganese and hexavalent chromium inside and outside of the welding helmet concentrations.

The welding helmet seemed to be protective for some metals, but it should not be assumed that protection will be provided by the use of it. As for sampling location for best welding fumes assessment monitoring, it is recommended that sampling is done outside. Welders often remove their welding helmets to verify the weld, and inside of the welding helmet sampling location may be compromised as it may change when the welding helmet is in the upward position.

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# DEDICATION

To my family, for their unconditional love, caring, and support throughout my life.

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# INTRODUCTION

Welders’ exposure to fume metals, fluorides, and particulate matter is unique. A variety of adverse health effects are associated with welding fume exposure including - asthma, decreased pulmonary function, respiratory tract infections, metal fume fever, and increase in cancer risk. Assessment of this exposure is performed inside the welding helmet as established by several agencies worldwide. Debate exists as to whether the inside of the welding helmet location is best for exposure assessment, instead of sampling outside of the welding helmet where the worst-case exposure is assumed. For this reason, the main purpose of this study was to determine which sampling location, whether inside or outside the welder’s helmet, is best to estimate a welder’s exposure to airborne particulates such as hexavalent chromium and individual constituents of welding fumes.

## Welding

According to the Bureau of Labor Statistics, at least 330,000 welding employees were registered working in the United States in 2012. Welding is utilized for metal union and fusion of pipes and others providing significant strength to metal unions. Welding settings can vary from vocational schools, fabrication shops, to the construction and shipyard industries. The use of stainless steel has become a popular design for architectural feature and is heavily used in the food and medical industry.

Welding is the process of joining metal parts usually permanently through the application of heat, fusion, or pressure of these metal parts. There are over 80 different types of welding processes (Villaume et al., 1979). Electric arc welding is the most common type of welding including shielded metal arc welding (SMAW), gas metal arc welding (GMAW) or metal inert gas (MIG), and gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) welding. Other types of welding include submerged arc welding, plasma arc welding, and oxygas welding. Electric arc welding utilizes a power supply to create the electric arc between the electrode and the base material that melt the metals in order to join them together.

Electrodes can be consumable or non-consumable. The welding area in the metal is usually isolated and protected from air by utilizing a shielding gas, vapor or slag. SMAW, also known as stick welding or manual metal arc welding (MMAW) utilizes a coating over the welding rod filler material which produces an environmental shield against oxygen and nitrogen degradation. The electrode is used as the filler material and the shield is produced during the electrode material decomposition. GMAW is the welding process where base metal pieces are joined using a continuous feed consumable electrode as the filler material where the weld is protected by a shielding gas, usually supplied externally. The electrode (or wire) is fed through a welding gun with a nozzle to provide the shielding gas. The shielding gas may be an inert gas or combination of gases. The metal electrode is fluidized by a high energy current which is then protected from oxygen by the inert shielding gas ejected from the welding nozzle. GTAW, also known as tungsten inert gas (TIG) welding is the process that uses a non-consumable tungsten electrode to create the weld. Usually, argon is utilized as the shielding gas while stainless steel welding rods are used as filler material. Arc current ranges from less than 50 to 500 amperes for GTAW. Generally, GTAW generates a lower airborne concentration of fumes when compared to GMAW (Kim et al., 2005). This is due to the transfer of the filler metal as spray. Shield gases include argon, helium, or a mixture of active gases including carbon dioxide. The flux-cored arc welding (FCAW) process is similar to GMAW in that the consumable electrode is utilized as the filler material, but the wire electrode has an internal flux material utilized for shielding. This process may or may not use a shielding gas (Antonini et al., 2004). Plasma arc welding (PAW) and FCAW exhibits the highest welding fumes exposure (Wallace et al., 2001).

According to the U.S. EPA, SMAW accounts for 45% of the total welding performed in the U.S., 34% can be accounted to GMAW, and 17% accounts for FCAW welding. It is believed that stainless steel accounts for only 5% of the welding done in the U.S. (IARC, 1990).

## Fume Properties

Welding fumes are generated when the molten filler material and base metal are unified. Oxidation and condensation happens due to the high temperatures to which the metal is exposed. Vapors from these chemical and physical reactions are released into the atmosphere due to the welding arc. Villaume et al. (1979) documented several factors affecting fume generation rate including welding process, current utilized, and wire and flux type. Welding fumes composition differs depending on the base metal components, metal coating, filler material, shield gas, consumable electrode, flux material, and the temperature used in the process (Zimmer and Biswas, 2001). Metals commonly found in welding fumes include aluminum, barium, beryllium, hexavalent chromium, chromium oxides, chromium, copper, iron oxide, lead, manganese, magnesium, molybdenum, nickel, and zinc oxides. Fumes contain silicates and fluorides generated from the electrode-coating emissions. Gases generated by welding include carbon monoxide, nitrogen oxide, and ozone (EPA, 1994).

Mild steel or carbon steel typically has an iron composition of more than 80% and a manganese composition of less than 15%. In addition to iron and manganese, stainless steel has a chromium composition of up to 30% and a nickel composition of up to 10%. Chung et al. (1999) reported welding fumes composition differences when comparing bulk area samples to personal samples collected on a mannequin. The authors reported an underestimation of welding fumes components when comparing samples to the manufacturer's composition material data sheet. In some studies, it was found the base metal played a less important role in fume generation when compared to the electrode type used and its composition (Antonini, 2003; Howden et al., 1988). Kim et al. (2005) reported lower welding fumes concentration ranging between 45 and 77 $\mu g/m^3$ for GTAW.

Fumes are solid particles formed by condensation from the gas state. These particles react with air when they are vaporized. Welding fumes particle sizes vary from 0.1 to 5 micrometers, categorizing fumes in the ultrafine and fine particle ranges (Voitkevich, 1995). The particles in this size range are of the respirable fraction. These particle sizes especially affect the lower respiratory tract including the bronchioles and alveoli (Antonini et al., 2004). Liden and Surakka (2009) described three modes of particle size distribution for aerosols produced while welding. Fumes less than 1 micrometer made up of oxidized metal vapors are the smallest. These particles are transported in the atmosphere by diffusion and other processes. The next mode includes spherical particles usually between 6 to 13 micrometers that have been solidified from the hot metal that is not oxidized (Liden and Surakka, 2009). The last mode includes fine and coarse particles that may be present if grinding is performed. Coarse particles are produced by mechanical processes when larger, solid particles are broken up.

Particle size distribution may change due to arc heat and agglomeration in the welding process (Clapp and Owen, 1977). The interaction between the agglomerated particles due to welding and the lung cells has not been studied in depth (Antonini et al., 2004). Zimmer and Biswas (2001) reported smaller mean particle diameters for GMAW process than the particles generated in FCAW. The GMAW particle morphology was a homogeneous chainlike agglomerate while the FCAW resulted in more spherical agglomerated particles (Zimmer and Biswas, 2001).

Liden and Surakka (2009) found that manganese had a particle size of less than 2 micrometers and constituted about 65% of the fume composition. In this study, manganese typically constituted less than 55% of total welding mass inhalable fraction. The study also reported that about 90% of the welding mass was less than 20 micrometers. Chung and Carter (1996) found that field samples were 225% higher when grinding operations were evaluated.

## Adverse Health Effects

Welding can pose serious health risks for workers performing the job. Particles less than one micrometer may be able to deposit deep into the lungs in the alveolar region, creating inflammatory pulmonary health effects. Metal toxicity has been associated with the metal oxidation state. Several health conditions that can be developed by welding fume exposure include metal fume fever, tightness in the chest, decreased pulmonary function, siderosis, upper respiratory infections, pneumonia, and suppression of the immune system (Boshnakova et al., 1989; Howden et al., 1988; Tuschl et al., 1997; Schoonover et al., 2010).

Pulmonary adverse health effects such as bronchitis prevalence among welders have been documented (Martin et al., 1997; Sferlazza and Beckett, 1991). Decreased lung function has been reported in several studies where confined spaces or areas lacking ventilation or with improper ventilation during welding (Akbar-Khanzadeh, 1980; Mur et al., 1985; Oxhoj et al., 1979). Schoonover et al. (2010) found 86% of the total welding fume mass composition was iron to which overexposure can cause siderosis. Also, welders were exposed to six times the manganese concentration and four times the aluminum, copper, and zinc concentrations than the non-welders. Metal fumes such as copper, cadmium, tin, and zinc can cause metal fume fever. Fluorides, barium, copper, and cadmium can cause lung irritation. Other metals in welding fumes such as lead and manganese are believed to cause neurological development impairment. Manganism or Welder's Disease occurs when exposure to high concentrations of manganese occurs. Manganese exposure may cause insomnia and fatigue as well. Promotion of redox reactions and creation of cytotoxic free radicals may be due to the oxidation and transition states of manganese and nickel (Antonini et al., 2004).

According to the International Agency for Research on Cancer (IARC, 1990; NTP, 2011), hexavalent chromium or Cr (VI) has been categorized as a potential carcinogen to humans (Group I) and welding fumes have been categorized as a Class 2B possible human carcinogen. Antonini et al. (2004) argues that lung cancer due to welding fumes exposure is inconclusive due to the difficulty in assessing exposure due to different welding settings, materials such as stainless steel welding in confined spaces, and additional carcinogens exposure. The United States Environmental Protection Agency (EPA) classifies Cr (VI) as a Group A carcinogen through the inhalation exposure route (EPA, 1998). Trivalent chromium has a lower toxicity level because it does not enter cells, while hexavalent chromium has been associated with mutagenic effects (Cohen et al., 1993; Maxild et al., 1978).

The relationship between lung cancer and Cr (VI) exposure remains unclear. Some studies suggest an excess risk of lung cancer and adverse health effects due to acute occupational exposure. However, other studies did not show a statistically significant correlation between lung cancer and the exposure (Danielsen et al., 2000; Hansen et al., 1996; Steenland et al., 1991). Confounded results of co-variables such as nickel, asbestos, or smoking have not been analyzed. Cr (VI) is also known for being an irritant to the respiratory tract and eyes (NTP, 2007). Recent studies have shown that Cr (VI) ingestion can cause cancer in the digestive tract (Chang et al., 1996). Other Cr (VI) health effects include skin sensitization and allergic contact dermatitis (Meeker et al., 2010; NTP, 2007; NTP 2008; Stout et al., 2009).

Stainless steel particles have been shown to remain in the lungs longer than mild steel particles and to have pneumotoxic properties (Antonini et al., 1996). Antonini et al. (2004) utilized animal models and toxicological studies to investigate lung injury and inflammation properties of welding fumes. The author found significant response of lung injury and inflammation and longer lung elimination time for stainless steel fumes. Antonini et al. (2004) concluded the high lung toxicity response could have been due to the increased macrophage production of oxygen radicals and inflammatory cytokines.

Ozone and nitrogen dioxide are generated as well in the welding process. Ozone is an irritant and can cause shortness of breath, wheezing, and pulmonary edema (Schoonover et al., 2010). At high concentrations, ozone can cause free radical production in the lungs (Peng et al., 2007). Nitrogen dioxide is produced in combustion where high temperatures can oxidize atmospheric nitrogen. An adverse health effect associated with nitrogen dioxide includes decrease in pulmonary function.

Other adverse health effects due to welding include eye and skin burns, electrical shocks, visual impairment, dermatitis from ultraviolet radiation exposure, and musculoskeletal disorders due to awkward positions when welding.

## Inside and Outside Welding Helmet Comparison Studies

Researchers have shown that sample concentrations collected outside the helmet generally tend to be higher than the inside-helmet samples (Blade et al., 2007; Goller and Paik, 1985). Johnson (1959) collected samples where outside concentrations were 3.5 times higher on average than inside of the welding helmet. Sentz et al. (1969) found outside of the helmet welding concentrations to be 40% higher than inside during arc-air operations. Goller and Paik (1985) found that average iron oxide concentrations outside of the helmet were between 1.4 and 2.8 times higher depending on where the sampling cassette inlet was placed. It was also found in the research that breathing zone samples taken inside the helmet were between 36% and 71% of the concentrations measured outside of the helmet (Goller and Paik, 1985). The authors concluded a welding helmet attenuation of 29% to 64%. However, Liu et al. (1995) found that 35% to 44% of the sample concentrations inside of the helmet were higher than those outside the helmet when sampling for iron and zinc.

Some studies debate whether the sampler location matters in term of a welder being left- or right-handed. Liu et al. (1995) and Chung et al. (1999) documented inside to outside concentration ratios of 1.07 to 1.13, but found that concentrations varied slightly depending on which side, left or right side of welding helmet the sampler was placed. Chung and Carter (1996) collected breathing zone samples. It was indicated in the research results higher concentrations on samples taken on the right-side than left-side, usually by 20% which implicate position may play a role when monitoring exposure. Harris et al. (2005) suggested that higher acute (or shorter) exposures have a higher variability when comparing inside to outside helmet concentrations. The authors found as well a significantly higher concentration outside the welding helmet than inside by 13%.

Flynn and Susi (2009) studied The Welding Institute (TWI) database. The TWI data set includes 1,929 welding samples collected through a 34 year period across the U.S., U.K., and Canada. A reduction of total welding fumes from placing the sampler inside of the helmet instead of outside was of about 50% for welding fumes, 23% reduction for iron, and no reduction difference when studying manganese concentrations. The Center for Construction Research and Training (CPWR) data set includes total particulate matter and manganese concentrations collected over a 12 year period under construction sampling events. The Occupational Safety and Health Administration (OSHA) data set includes 5,339 compliance samples collected over a 30 year period. All three TWI, OSHA, and CPWR database study sets exhibited high concentrations in manganese of over 0.2 mg/m$^3$ as reported by Flynn and Susi (2009).

Boelter et al. (2009) collected a variety of samples including total particulates, manganese, and iron inside and outside the welding helmet. A 15% difference was found between the two sample locations. In 2007, NIOSH conducted an exposure assessment where Cr (VI) concentrations measured outside the helmet were from 2 to 5 times higher than the recommended exposure limit (REL) for a welder performing metal inert gas (MIG) welding. Iron and manganese concentrations were higher when sampled outside of the helmet for most of their samples, and a 15% difference between inside and outside of the helmet concentrations for long-term samples (over 15 minutes) were reported in the study. Iron composition varied from 10% to 20% of the samples.

## Breathing Zone

The breathing zone according to the Occupational Safety and Health Administration (OSHA) is within a ten inch radius of the worker's nose and mouth or the area immediately adjacent to the employee's nose and mouth; a hemisphere forward of the worker's shoulders with a radius of approximately 6 to 9 inches or the 18-inch diameter sphere around the employee's head. Similarly, the American National Standards Institute (ANSI) Standard 62.1-2004 also defines breathing zone within these parameters. OSHA requires that worker exposure monitoring air samples be collected in the breathing zone. Air sampling filters may be attached to the collar or lapel. However, for welding tasks the OSHA Technical Manual 1:1-9 specifies the sampling location as inside of the welding helmet.

The American Industrial Hygiene Association (AIHA) defines the breathing zone as the volume surrounding a worker's nose and mouth from which he or she draws breathing air over the course of a work period with a 10-inch sphere radius centered at the worker's nose (Dinardi, 1997). The European Committee for Standarization (CEN) defines the breathing zone as the space around the worker's face from where he takes his breath. For technical purposes, a more precise definition offered by CEN is described as a "hemisphere (generally accepted to be 0.98 ft in radius) extending in front of the human face, centered on the mid point of a line joining the ears; the base of the hemisphere is the plane through this line, the top of the head and the larynx". The definition is not applicable when respiratory protection equipment is used (CEN, 1998).

Liden and Surakka (2009) mentioned the inconsistency of concentration measurements when the worker is close to the source from no significant difference in concentration to concentrations up to four times higher (Guffey et al., 2001; Malek et al., 1999; Parker et al., 1990; Rosen et al., 1997, Welling et al., 2000). An argument of the Liden and Surakka (2009) study is the unspecified sampling location when sampling for welding fumes, whether the filter placement is best set in the left or right side of the welding helmet, or if any other location would serve best as sampling location. The researchers developed a headset model based on commercial headsets with professional microphones which were placed over the ears with a headband locating the microphone near the mouth and nose region. In this study, it was demonstrated that an aerosol sampler mounted on the headset behind the welding helmet is feasible and does not interfere with the welder. The sampler was able to be positioned close to the nose and mouth area independently of the welding helmet position. A consideration when placing the sampling device or filter on the welder is whether the sampler placement is comfortable. Welders complained about the pressure made by the headset model pressing into the head bone or skull and the obstacles faced when other developed headsets were used (Liden and Surakka, 2009).

Several researchers have addressed positioning the sampling device at other locations or with other techniques. Chien (1992) suggested an ear mounted tube where the sampler would be close to the nose area. Allen et al. (1981) investigated another mounted tube on the helmet's headband later modified by the U.K. Health and Safety Laboratory for the sampler to be closer to the eyes area. Simpson (2005) studied both locations and found that concentrations taken at the eyes area were 50% higher than those taken closer to the mouth area. Also, Chung et al. (1999) stated that standards do not define side position placement or sampler placement on the face shield. Chung et al. (1990) found that samplers on the left side collected greater fumes concentrations than those placed in the right side when the mannequin was right-sided. Also, the lapel samplers collected greater fumes concentration than those placed in the personal breathing zone. In this study, it was concluded the need for further studies in order to establish sampler placement appropriate location.

## Personal Protective Equipment

According to the American Welding Society, some of the hazards associated with welding and cutting include sparks, spatter, radiation (infra-red, ultra-violet, and blue light), slag, heat, hot metal, fumes and gases, and electric shock. The special requirements for the welding helmet include a visual screen with filter lens and cover plate complying with the ANSI Z87.1 standard which would protect specifically from radiant energy such as UV light emitted from the welding arc, flying sparks, and spatter; such as the use of a face shield, welding helmet, and safety glasses. Both OSHA, in section 29 Code of Federal Regulation (CFR) 1910.252 and ANSI, in standard Z49.1 require that helmet and hand protection are utilized so that the face, forehead, neck, and ears are protected. Foot protection may vary from a fire-resistant material and steel-toe shoes and should follow the American Society for Testing and Materials (ASTM) F2412 and ASTM F2413 standards. ASTM suggests wearing a leather apron and welding gloves. ANSI Z49.1 requires using respiratory protection in confined spaces and when fluorine compounds are present and when ventilation is not feasible.

## Occupational Exposure Limits

For welding fumes, the American Conference of Governmental Industrial Hygienists (ACGIH) has established an 8-hour time-weighted average (TWA) of 5 $mg/m^3$ as total particulates measured inside of the welding helmet. OSHA does not currently regulate welding fumes. The OSHA regulation for hexavalent chromium (Cr VI) is specified in the Standard Code of Federal Regulations (CFR) 1910.26 Appendix A. It is state in the standard that an industry with a hexavalent chromium concentration at or over 0.5 $\mu g/m^3$ as a TWA requires air monitoring for this agent. If an employee exposure exceeds the OSHA permissible exposure limit (PEL), respiratory protection is required. OSHA reduced the Cr (VI) PEL to an 8-hour TWA of 5 $\mu g/m^3$. The new action level (AL) has been established to be at 2.5 $\mu g/m^3$ for an 8-hour TWA. However, the National Institute for Occupational Safety and Health (NIOSH) has recently reduced the recommended exposure limit (REL) of Cr (VI) to 0.2 $\mu g/m^3$ based on a 8-hour TWA.

## Welding Fumes Exposure

Personal samples of welding concentrations in the in the breathing zone varied from < 1 $mg/m^3$ to 5 $mg/m^3$, in some cases, concentrations were higher. Ulfarson (1981) found that welding concentration ranges varied from 100 $mg/m^3$ up to 400 $mg/m^3$ in the welding arc region. Welding fumes exposure is fairly unique (Antonini et al., 2004). NIOSH and ACGIH both have set limits for welding fumes, but because of welding fumes' different constituents, it is difficult to set new limits and agencies have had to address this issue by setting limits for individual fumes (ACGHI, 2001; NISOH, 1992).

Tharr et al. (1997) collected welding fumes samples in the breathing zone of welders. The sample constituents did not exceed the occupational exposure limits (OEL) for welding fumes, lead, total chromium, nickel, cadmium, and zinc. For six manganese samples, the personal samples exceeded threshold limit value (TLV). Wallace et al. (2001) also reported overexposure to hexavalent chromium, arsenic, total chromium, iron, manganese, and nickel. Flynn and Susi (2010) found a strong correlation between manganese and total particulate as well as with iron. Correlation coefficients were greater than 0.7 based on the TWI data set #2. This correlation could have been due to the composition of total welding fume being over 60% iron.

Linden and Surakka (2009) reported that for manganese, welders' exposures ranged from 0.65 to 0.73 mg/m$^3$. In this study, five welders exceeded the manganese threshold limit value (TLV) of 0.2 mg/m$^3$ for almost all of the personal shift samples. Meeker et al. (2010) reported hexavalent chromium concentrations exceeding the PEL by 9%, 13%, and 25%, when the OSHA Data Set, TWI Data Set, and the CPWR Data set were analyzed, respectively. Hobson et al. (2011) developed five models for manganese welding fumes prediction. It was concluded that the two major predictors for manganese welding fume generation include welding process and degree of enclosure. Wallace et al. (2001) reported overexposure to hexavalent chromium, arsenic, total chromium, iron, manganese, and nickel. Flynn and Susi (2010) also analyzed the CPWR dataset concluding that boilermakers were more exposed to these hazards than pipefitters or ironworkers.

Correlation analyses among metals, welding fumes, and total particulates have been performed. Weak to moderate correlations were found between Cr (VI) and total particulate mass TWI Data Set analyzed by Meeker et al. (2010). A stronger correlation was present when only stainless-steel welding was analyzed, which could have been attributed to the composition of total mass and fumes.

Keane et al. (2012) reported high variation for fume generation rates. Hexavalent chromium generation rates were higher than previously reported. Also, a correlation between Cr (VI) generation rate and Cr (VI) fume content could not be found. Some observed high concentrations were assumed to be caused by work practices since no other variables could be attributed for the high concentrations.

Schoonover et al. (2010) studied exposure to both ozone and nitrogen dioxide. The samples were collected outside of the welding helmet with passive diffusion samplers. Welders were exposed to 50 ppb of nitrogen dioxide, in comparison to 37 ppb $NO_2$ for non-welders exposure, which was not statistically significant. Also, welders were exposed to 7.3 ppb of ozone, in comparison to 3.2 ppb for non-welder exposure. It was in the study noticed the maximum concentration for both $NO_2$ and $O_3$ were almost three times higher in welders than non-welders. Liu et al. (2005) documented exposure concentrations of 46.2 ppb and 2.6 ppb for nitrogen dioxide and ozone, respectively.

## Engineering Controls

Tharr et al. (1997) were able to assess ventilation at a vocational institution where welding was done. The authors documented that a visible haze was present throughout the welding shop. Minimal capture of a smoke released for ventilation testing performance was documented in this study. Personal samples taken in the afternoon classes were higher in average than samples taken in the morning classes, which the authors speculated to be due to ventilation malfunction and higher fume concentration background in the afternoon. Further tests showed that out of the three exhaust fans, only one was properly functioning. Another finding in this study included the improper use of the local exhaust ventilation since the distance was inappropriate for fume capture. In some occasions, the fumes had to pass by the students' breathing zones in order to be captured by the local exhaust ventilation system. None of the welding fume metals exceeded the OSHA PEL, but some exceeded the ACGIH TLV.

Wallace et al. (2002) concluded that the use of ventilation reduced exposure by almost 50% when properly used. The use of local exhaust ventilation (LEV) reduced the total particulate mass exposure by 35%. Zaidi et al. (2004) documented a reduction of manganese from 22.2 to 8.2 μg/m$^3$ when local exhaust ventilation (LEV) was utilized.

The use of ventilation was more effective for pipefitters reducing manganese concentrations by 12% as compared to when LEV was not utilized (Flynn and Susi, 2009). Although ventilation is used to reduce exposure, it was found in this study that in one event, the exposure was actually increased due to ventilation. From the TWI data set #2, Flynn and Susi (2009) concluded that LEV reduced exposure by 35% (3.01 mg/m$^3$ with LEV use and 4.61 mg/m$^3$ without LEV) where manganese and iron concentrations were also reduced by 31% and 41%, respectively. Analysis of the CPWR data set as well indicted that ventilation reduced total welding fumes and manganese by 20% and 12%, respectively. Mechanical ventilation consisting of fans and blowers with the intention to blow away or disperse fumes was investigated in this study. It was documented that the mechanical ventilation reduced total particulate by 72%, but it also increased exposure of both total particulate by 64% and four times the manganese concentration at a different facility. Boelter et al. (2009) documented higher concentrations both in personal sampling and area samples in more confined spaces such as a boiler room than a breezeway attributing this result to a more diluted atmosphere. A significant increase in concentrations when fans were used for mixing was reported in this study. Additionally, it was described in this study a chaotic welding fume plume when the fans were in use. The researchers also warned about the fans' positions if these are intended for plume dilution and ventilation control. Chung et al. (1999) purposely utilized fans to increase the rate of fume collection when the fan was placed directly on a mannequin. It may be speculated that aerodynamics played a role in this particular case. In general, mechanical ventilation did reduce welders' exposures, but in some cases, it increased the exposures.

Meeker et al. (2010) concluded that Cr (VI) concentrations from the TWI database, which included 1,926 samples taken from 1973 to 2007, were greater by 13% when the LEV systems were not used. The analysis performed with the CPWR database revealed a reduction in the mean samples measured in the breathing zone (Meeker et al., 2010). The analyzed samples were collected between 2007 and 2008 for a total of 43 samples from boilermakers and pipefitters welders and were categorized in controlled welding trials database to test LEV efficiency (Meeker et al., 2010). Meeker et al. (2010) concluded no statistical significance when comparing LEV use utilizing the CPWR Data Set field survey. TWI Data Set analysis on hexavalent chromium concentrations were reduced by almost 5 times utilizing LEV (Meeker et al., 2010). When SMAW process was analyzed, Cr (VI) concentrations were reduced by 19%. The CPWR data was also analyzed for controlled-welding trials on LEV effectiveness and reported a statistically significant concentration reduction of 55%.  In general, LEV effectively reduced welding fumes exposure when properly utilized.

Welding fumes exposure can vary greatly depending on factors such as welding process, electrode utilized, and LEV proper use among other factors.  Welding fumes exposure assessment is performed in the breathing zone region.  The objective of this research project was to investigate if there is a statistically significant difference between the samples collected inside of the welding helmet and the outside of the welding helmet. Since OSHA requires welding fumes exposure to be assessed inside of the welding helmet, it is of interest to investigate if this sampling location is appropriate, or if concentrations outside of the welding helmet would provide a more reliable assessment.

# METHODS

A field-based exposure assessment was conducted over a period of nine months to investigate the difference between welding fumes concentrations inside and outside the welding helmet. Two companies participated in this study. One set of workers employed by a manufacturing company specializing in food and medical industry supplies will be referred to as Company 1. The other set of workers employed by a brewing company on maintenance and improvement tasks will be referred to as Company 2.

A total of 54 samples were taken, a pair of fifteen samples for hexavalent chromium and a pair of twelve samples for welding fumes. Welders were sampled once. No repeated measurements were taken per welder sampled. Welding sampling duration per welding task lasted from 58 to 400 minutes. No specific respiratory protective equipment was worn by the majority of the welders, except for one welder who was wearing a powered air purifier respirator (PAPR). Types of welding helmets varied as some of the welders used their own purchased helmet as shown in Figure 1.

GTAW was the welding process performed among the sampled welders. The shielded gas utilized by the welders was argon. Company 1 used 304 welding rods, while Company 2 used 316L rods.

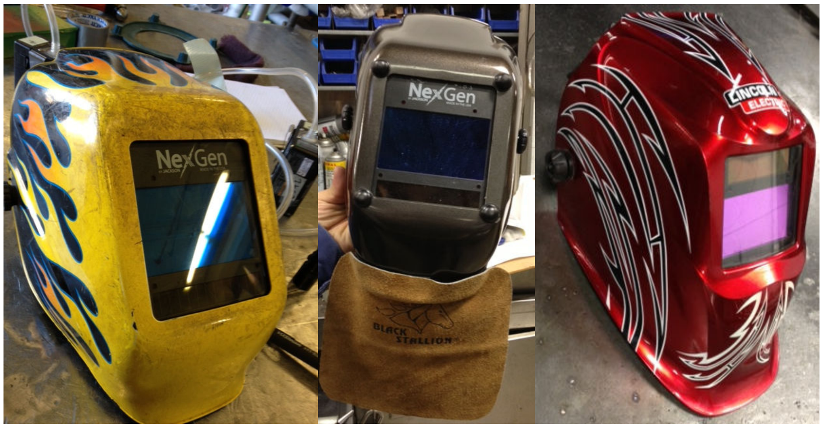

Figure 1. Different Welding Helmets Used by the Welders

Hexavalent chromium personal air samples were taken on 15 different workers, while welding fumes samples were taken on 12 different workers. Only stainless steel TIG welding was sampled to maintain consistency among the sampling. All aspects of this research were conducted in accordance with procedures approved by the Colorado State University (CSU) Institutional Review Board (IRB) and the Research Integrity and Compliance Review Office.

Pumps utilized were MSA Escort Electronic Laminar Flow (ELF) personal sampling pumps (Pitts, PA) and were calibrated to a flow rate of 2 L/min at a laboratory with a BIOS Dry Cal (Butler, NJ). The pumps were pre- and post- calibrated. A sampling train was assembled to collect hexavalent chromium and welding fumes. The sampling train consisted of a calibrated pump, tygon tubing, and an open-faced or closed-faced 37 mm filter cassette. The tygon tubing connected the pump to the cassette allowing for air suction through the cassette. The sampling cassettes and filter media were placed in the breathing zones of the workers. Inside of the welding helmet, sampling medium (open-faced filter cassette for hexavalent chromium, closed-faced filter cassette for welding fumes) was usually placed next to the eye screen of the helmet. On a few occasions, the filter medium for collection on the inside of the welding helmet was placed below the cheek, closer to the mouth area as shown in Figure 2. Outside of the welding helmet, the sampling medium was attached to the shirt collar or jumpsuit as shown in Figure 3.

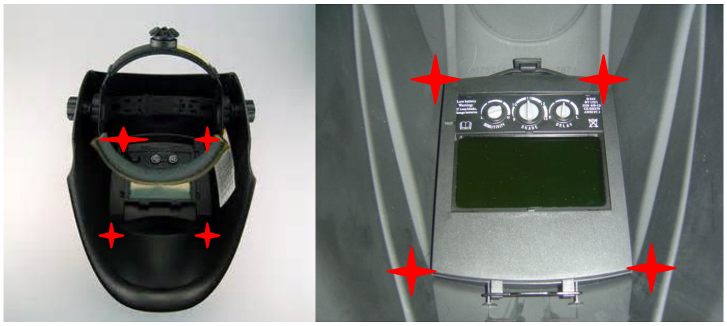

Figure 2. Various sampling locations inside the welding helmet. The red crosses indicate the various sampling locations where the media was placed in order to collect the inside of the welding helmet samples. The media was usually placed either on top of dark screen or in the area closer to the jaw line inside of the welding helmet.

The inside and outside of the helmet samples were simultaneously collected for hexavalent chromium and welding fumes, but hexavalent chromium and welding fumes were evaluated on different welding days. This was done for welder comfort so that they would have only the burden of two sampling pumps instead of four sampling pumps while welding. Since the sampling was performed during actual welding tasks and not an experimental setting, it was in the best interest for the welders to be comfortable and allow them to be able to perform their welds as similar to their daily practice as possible. Samples were only taken when welders were welding. Pumps were paused when tasks such as grinding, cutting, and polishing were performed. However, welders may have briefly performed grinding or cutting while the pumps were running.

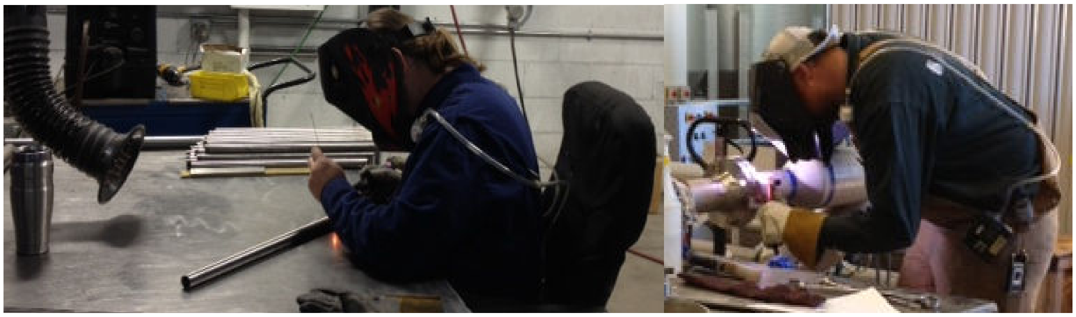

Figure 3. Typical Sampling Scenario for Welding Fumes.

Hexavalent chromium samples were collected on a 37-mm diameter polyvinyl chloride (PVC) filter (5 µm pore size) contained in a open-faced polystyrene cassette (Na/K/Cr6 media) and analyzed by the Wisconsin Occupational Health Laboratory (WOHL) method WI008hex.14 based on the OSHA Method ID-215 version 2 utilizing ion chromatography. Samples were analyzed by in-house method Elastohydrodynamic (EHD) Metals Method 400.2 rev.3 based on EPA 200.7 and SW846 6010B.

Welding fumes were collected on a mixed cellulose ester (MCE) filter 0.8 micrometer (white band labeled AA media) closed-faced cassette and analyzed by WOHL. Samples were digested for metals analyzed by the WOHL in-house method EHD Metals Method 001 rev.3, which is based on NIOSH Analytical Method (NMAM) 7303 utilizing Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Total welding fumes concentration were calculated in addition to individual metals analysis. The metal analysis scan included aluminum welding fumes, boron, barium, total chromium (metal and insoluble), copper fume , cadmium fume, cobalt (as metal, fume, dust), iron oxide fume, lead inorganic fume and dust, magnesium oxide fume, manganese fume (as Mn), molybdenum (insolubles), nickel, and zinc oxide fume. A blank or two blanks were collected on sampling days depending on the amount of samples taken during the day. Collected samples were shipped to WOHL within a week of the sampling day.

Comparison among welding studies and exposure assessment are difficult (Antonini et al., 2004). A priori power analysis for the difference between two dependent means (matched pairs) or a Wilcoxon signed-rank test (for matched pairs) was based on two different available data sets, Goller and Paik (1985) and Liu et al. (1995). The software utilized to perform the power calculation was G Power version 3.1 software. According to the Goller and Paik (1985) published data, 8 to 17 paired samples would have been needed for an alpha of 0.05 and a statistical power between 80 to 95%, where iron oxide fumes were sampled. Utilizing the published zinc oxide fumes data by Liu et al. (1995), a total of 44 to 96 paired samples would have had to be collected for an 80 to 95% statistical power analysis, respectively.

Post-hoc statistical power analyses were performed for each metals species. For hexavalent chromium, only a power of 15% could be obtained probably due to an outlier that was obtained for one paired sample. For a power of 80 to 95%, at least 60 to 90 paired samples needed to be collected. Samples that were below the limit of detection (LOD) were removed as well as the outlier, a statistical power of 94% was achieved with the 8 paired samples.

For welding fumes, a power of 70% was achieved when all paired samples were considered for the analysis. For total chromium, when concentrations below the limit of detection were removed, the statistical power was calculated at 63%. A total of 12 paired samples would have provided a power of over 80%. Iron paired samples had a 67% statistical power. For a 90% statistical power, 20 paired samples would have been needed. Nickel paired samples had a 70% statistical power. Paired samples of 15, would have had a power of 80%. For manganese, a statistical power of 95% was calculated for the 12 paired samples.

All of the concentrations analyzed for cadmium, aluminum, lead, zinc, copper, and magnesium were lower than the LOD. For this reason, these metal species were discarded from the analyses. Only paired samples above the LOD (n = 8, paired samples) for the metal fumes included in the statistical analysis were utilized as it was not possible to determine which sample, inside or outside of the welding helmet was greater or the specific difference between samples. For the metals analyzed, 8 and 12 analyzed samples were discarded for total chromium and for hexavalent chromium, respectively. LOD concentrations were calculated by WOHL based on the volume calculated from the flow rate provided and utilizing the mass reporting limit for the metal (Appendix A). Also, an outlier was found in a hexavalent chromium sample set. The set was not eliminated as both inside and outside concentrations exhibited unusually high concentrations when compared to the other sample sets. Statistical analysis was performed including the outlier and excluding the outlier to investigate differences in results.

First, the sample concentrations were tested for normality. Tests for normality included skewness, kurtosis, Shapiro-Wilk, histograms and Q-Q plots. If the normality tests performed on the various metals failed, concentrations were transformed to natural logarithm values. If the normality tests failed with the log-transformed concentration values, it was concluded that the sample concentrations were not normally distributed, and therefore, a Wilcoxon nonparametric test was performed to analyze the concentration difference between the inside and outside of the welding helmet samples. If the concentration difference was normal, a Student Paired t-test was utilized to analyze the concentration difference.

Microsoft Office Excel 2003 software was utilized to perform the descriptive statistics analysis. This analysis included calculating the mean, median, standard deviation, and standard error. Mean and median concentrations were calculated in order to investigate the differences due to large concentration range among the metals analyzed. The R Commander version 2.15.2 software was utilized to perform the normality tests, distribution tests, Student Paired t-test, Wilcoxon Sign-Rank order test, and the Spearman's rank-order correlation test.

# RESULTS

Personal air samples were sampled simultaneously inside and outside of the welding helmet for concentration comparison of welding fumes (n = 24) and hexavalent chromium (n = 30). A total of fifteen welders were sampled in a manufacturing setting and a brewery for a total of 27 inside and outside of the welding helmet paired samples. Hexavalent chromium descriptive statistics are shown in Table 1. Hexavalent chromium concentration values were not found normal or lognormal, therefore, a nonparametric analysis was utilized.

Table 1. Hexavalent Chromium Descriptive Statistics

| **Metal Fumes** | | **n** | **Sampling Duration Range (min)** | **Mean (μg/m$^3$)** | **Median (μg/m$^3$)** | **Standard Deviation (μg/m$^3$)** |
|---|---|---|---|---|---|---|
| Hexavalent Chromium | Inside | 15 | 58 - 314 | 2.98 | 0.25 | 11.2 |
| | Outside | 15 | 58 - 316 | 9.51 | 0.2 | 37.4 |
| Hexavalent Chromium (no outlier) | Inside | 14 | 74 - 314 | 0.208 | 0.235 | 0.0992 |
| | Outside | 14 | 74 - 316 | 0.203 | 0.185 | 0.0989 |

Inside the welding helmet concentrations for hexavalent chromium varied from 0.081 to 42 μg/m$^3$ when the outlier was included as shown in Table 1. The hexavalent chromium inside concentration mean was 2.98 μg/m$^3$ and the outside concentrations mean was 9.51 μg/m$^3$. Outside the welding helmet concentrations for hexavalent chromium varied from 0.08 to 140 μg/m$^3$ when an outlier was included. Without the outlier, the maximum concentration inside and outside of the welding helmet were 0.34 μg/m$^3$ and 0.40 μg/ m$^3$, respectively. The median concentration was about 0.2 μg/m$^3$ for both inside and outside concentrations with or without the outlier. The median inside concentration was higher than the outside median for hexavalent chromium.

The means, medians, and standard deviations for inside and outside concentrations of total chromium, manganese, iron oxide, nickel, and total welding fumes are shown in Table 2.

Table 2. Individual and Total Welding Fumes Descriptive Statistics

| **Metal Fumes** | | **n** | **Sampling Duration Range (min)** | **Mean ($mg/m^3$)** | **Median ($mg/m^3$)** | **Standard Deviation ($mg/m^3$)** |
|---|---|---|---|---|---|---|
| Total Welding Fumes | Inside | 12 | 94 - 400 | 0.135 | 0.123 | 0.0947 |
| | Outside | 12 | 95 - 400 | 0.209 | 0.197 | 0.121 |
| Iron | Inside | 12 | 94 - 400 | 0.102 | 0.0875 | 0.0769 |
| | Outside | 12 | 95 - 400 | 0.162 | 0.155 | 0.1 |
| Nickel | Inside | 12 | 94 - 400 | 0.00708 | 0.006 | 0.00507 |
| | Outside | 12 | 95 - 400 | 0.0116 | 0.0112 | 0.0074 |
| Total Chromium | Inside | 12 | 94 - 400 | 0.0179 | 0.0155 | 0.00942 |
| | Outside | 12 | 95 - 400 | 0.0263 | 0.024 | 0.0149 |
| Manganese | Inside | 12 | 94 - 400 | 0.00803 | 0.0046 | 0.0116 |
| | Outside | 12 | 95 - 400 | 0.00953 | 0.00635 | 0.0121 |

The mean concentrations values for all the welding fume metals analyzed were found to be from 0.007 mg/ $m^3$ to 0.21 mg/ $m^3$. The median concentrations were found to be from 0.0046 mg/ $m^3$ to 0.197 mg $m^3$. The standard deviations for all the welding fume metals were found to be from 0.005 mg/ $m^3$ to 0.095 mg/ $m^3$. Outside concentrations were typically higher than inside of the welding helmet concentrations. Values for the statistical parameters were higher for outside of the welding helmet concentrations than inside concentrations.

A statistically significance difference ($p = 0.05$) between the inside and outside welding helmet concentrations was found for total welding fumes, iron, total chromium, and nickel, where outside concentrations were found higher than inside of the welding helmet concentrations. A Student Paired t-test for parametric values was utilized when analyzing manganese samples and a Wilcoxon nonparametric test was utilized when analyzing hexavalent chromium, total chromium, nickel, iron, and total welding fumes.

Hexavalent chromium and manganese concentrations were not statistically significantly different ($p = 0.05$) when comparing inside and outside welding helmet concentrations as shown in Table 3 and Table 4. The concentrations means and medians values were within the confidence interval (CI) range.

Table 3. Comparison of Hexavalent Chromium Concentrations Statistical Analysis Results

| **Metal Fume** | | **n** | **Variance $(\mu g/m^3)^2$** | **CI $(\mu g/m^3)$** | **Concentration Range $(\mu g/m^3)$** | **p-value/test ($\alpha = 0.05$)** |
|---|---|---|---|---|---|---|
| Hexavalent Chromium | Inside | 15 | 116 | 0 - 8.63 | 0.081 - 42 | 0.68/ Wilcoxon |
| | Outside | 15 | 1300 | 0 - 28.4 | 0.08 - 140 | |
| Hexavalent Chromium (no outlier) | Inside | 14 | 0.00984 | 0.156 - 0.26 | 0.081 - 0.34 | 0.68/ Wilcoxon |
| | Outside | 14 | 0.00977 | 0.151 - 0.254 | 0.08 - 0.40 | |

Table 4. Individual and Total Welding Fumes Statistical Analysis Results

| **Metal Fumes** | | **n** | **Variance $(mg/m^3)^2$** | **CI $(mg/m^3)$** | **Concentration Range $(mg/m^3)$** | **p-value/test ($\alpha = 0.05$)** |
|---|---|---|---|---|---|---|
| Total Welding Fumes | Inside | 12 | 0.00897 | 0.0811-0.188 | 0.039 - 0.377 | 0.0049/ Wilcoxon |
| | Outside | 12 | 0.0147 | 0.141-0.278 | 0.0743 - 0.406 | |
| Iron | Inside | 12 | 0.00591 | 0.058-0.145 | 0.022 - 0.3 | 0.0015 Wilcoxon |
| | Outside | 12 | 0.00999 | 0.105-0.218 | 0.055 - 0.32 | |
| Nickel | Inside | 12 | $2.57 \times 10^{-5}$ | 0.00421-0.00994 | 0.0026 - 0.02 | 0.00098/ Wilcoxon |
| | Outside | 12 | $5.48 \times 10^{-5}$ | 0.00745-0.0158 | 0.0035 - 0.025 | |
| Total Chromium | Inside | 12 | $8.87 \times 10^{-5}$ | 0.0125-0.0232 | 0.0085 - 0.043 | 0.014/ Wilcoxon |
| | Outside | 12 | 0.000222 | 0.0179-0.0348 | 0.01 - 0.055 | |
| Manganese | Inside | 12 | 0.000133 | 0.00150-0.0146 | 0.0008 - 0.043 | 0.14/ Student t-test |
| | Outside | 12 | 0.000147 | 0.00268-0.0164 | 0.001 - 0.047 | |

For total welding fumes composition, the largest fume content found in the total welding fumes samples inside and outside of the welding helmet was iron, following total chromium, nickel, and manganese, which had the smallest welding fume content as shown in Table 5. One sample set for hexavalent chromium exceeded the PEL, REL, and TLV as shown in Table 6.

Table 5. Individual and Total Welding Fumes Inside and Outside Concentration Comparison: Metal Composition, Inside Samples Greater than Outside Samples, Factor Difference, and Helmet Attenuation

| **Metal Fumes** | **n** | **Metal Fumes Composition** | **Inside Samples Concentration > Outside Samples Concentration** | **Helmet** Attenuation %** |
|---|---|---|---|---|
| Hexavalent Chromium | 30 | N/A* | 4 | -50 - 70 |
| Hexavalent Chromium (no outlier) | 28 | N/A* | 4 | -50 - 26 |
| Total Welding Fumes | 24 | N/A* | 0 | 2 - 80 |
| Iron | 24 | Inside: 56-77%<br>Outside: 55-80% | 1 | -1 - 82 |
| Nickel | 24 | Inside :3.5-8.2%<br>Outside: 3.6-7.2% | 1 | 9 - 83 |
| Total Chromium | 24 | Inside: 12.7-33.3%<br>Outside: 11.9-16.8% | 0 | 0 - 75 |
| Manganese | 24 | Inside: 2-26.6%,<br>Outside: 1.3-28% | 2 | -84 - 63 |

*N/A=Not Applicable

**Negative values in helmet attenuation indicate values where inside of the helmet concentrations were greater than outside of the welding helmet concentrations.

Samples below the LOD for hexavalent and total chromium were taken into account in Table 5 and Table 6. When the LOD samples were removed, three hexavalent chromium samples and one total chromium sample inside of the welding helmet concentrations were greater than outside. When the LOD samples were removed, iron fume content ranged from 74 – 81%, total chromium fume content ranged from 11 – 18%, nickel fume content ranged from 5 – 6.2%, and manganese fume content ranged from 1.5 – 4.7% for both inside and outside of the welding helmet fumes content percentage.

Table 6. Individual and Total Welding Fumes Inside and Outside Mean Difference and 8-hr Time-Weighted Average

| **Metal Fume** | **n** | **8-hr TWA Concentration Range Inside and Outside (mg/m$^3$)** | **OSHA PEL (mg/m$^3$)** | **NIOSH REL (mg/m$^3$)** | **ACGIH TLV (mg/m$^3$)** |
|---|---|---|---|---|---|
| Hexavalent Chromium | 30 | Inside: 0.0000513 – 0.00508<br>Outside: 0.0000513 – 0.0169 | 0.005 | 0.0002 | 0.01 |
| Hexavalent Chromium (no outlier) | 28 | Inside: 0.0000513 - 0.00012<br>Outside: 0.0000513 - 0.000165 | 0.005 | 0.0002 | 0.01 |
| Total Welding Fumes | 24 | Inside: 0.0129 - 0.237<br>Outside: 0.0257 - 0.252 | 15 | Not Established | 5 |
| Iron | 24 | Inside: 0.007 - 0.189<br>Outside: 0.018 - 0.2 | 10 | 5 | 5 |
| Nickel | 24 | Inside: 0.0011 - 0.0126<br>Outside: 0.00119 - 0.0138 | 1 | 0.015 | 0.1 |
| Total Chromium | 24 | Inside: 0.004 - 0.027<br>Outside: 0.004 - 0.0298 | 1 | 0.5 | 0.5 |
| Manganese | 24 | Inside: 0.000265 - 0.0088<br>Outside: 0.00033 - 0.0093 | 5* | 1 | 0.2 |

*Ceiling Limit

## Samples below the Limit of Detection Statistical Re-Analysis

Six paired sample sets for hexavalent chromium were lower than the LOD. Re-analysis of the sample sets was performed without the values below the LOD. Inside the welding helmet concentrations (n = 9) for hexavalent chromium varied from 0.094 to 42 μg/m$^3$ when the outlier was included. Descriptive statistical results for hexavalent chromium and total chromium are shown in Table 7.

Table 7. Hexavalent Chromium Descriptive Statistics Re-Analysis Results without the LOD Values

| Metal Fume | n | Sampling Duration Range (min) | | Mean (µg/m$^3$) | | Median (µg/m$^3$) | | Standard Deviation (µg/m$^3$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | *Inside* | *Outside* | *Inside* | *Outside* | *Inside* | *Outside* | *Inside* | *Outside* |
| Hexavalent Chromium | 18 | 58-264 | 58-264 | 4.87 | 15.7 | 0.28 | 0.2 | 13.9 | 46.6 |
| Hexavalent Chromium (no Outlier) | 16 | 74-264 | 74-264 | 0.232 | 0.222 | 0.265 | 0.185 | 0.107 | 0.109 |
| Total Chromium | 16 | 151-400 | 153-400 | 19.9 | 32.6 | 17.5 | 30.0 | 10.7 | 14.2 |

Hexavalent chromium and manganese inside and outside concentrations were still not found statistically significantly different as presented in the statistical re-analysis in Table 8.

Table 8. Hexavalent Chromium Statistical Re-Analysis Results without the LOD Samples

| Metal Fume | n | Variance (µg/m$^3$)$^2$ | | Concentration Range (µg/m$^3$) | | CI (µg/m$^3$) | | p-value/ test ($\alpha = 0.05$) |
|---|---|---|---|---|---|---|---|---|
| | | *Inside* | *Outside* | *Inside* | *Outside* | *Inside* | *Outside* | |
| Hexavalent Chromium | 18 | 194 | 2170 | 0.094 - 42 | 0.12 - 140 | 0.1-0.34 | 0.13-0.4 | 0.73/ Wilcoxon |
| Hexavalent Chromium (no outlier) | 16 | 0.0115 | 0.0118 | 0.094 - 0.34 | 0.12 - 0.4 | 0.094-0.34 | 0.12-0.4 | 0.78/ Wilcoxon |
| Total Chromium | 16 | 0.114 | 0.203 | 8.5 - 43 | 11 - 55 | 12.5 - 27.3 | 22.8 - 42.5 | 0.0078/ Wilcoxon |

For total welding fumes composition, the largest fume portion found in the total welding fumes samples inside and outside of the welding helmet was iron with a percentage range of 14% to 80%. The smallest fume portion was manganese concentrations with a percentage range from

2 to 5%. Total chromium range was between 11 to 18% and nickel concentrations range was from 5% to 6%.

No statistically significant correlation was found between individual metal fumes concentrations and sampling duration as shown in Figure 4. When metals were analyzed with Spearman rank-order correlation, metal fumes including nickel, total chromium, and iron correlated with each other with the exception of manganese as shown in Figure 5. Additional figures of correlation among metal fumes can be found in Appendix B.

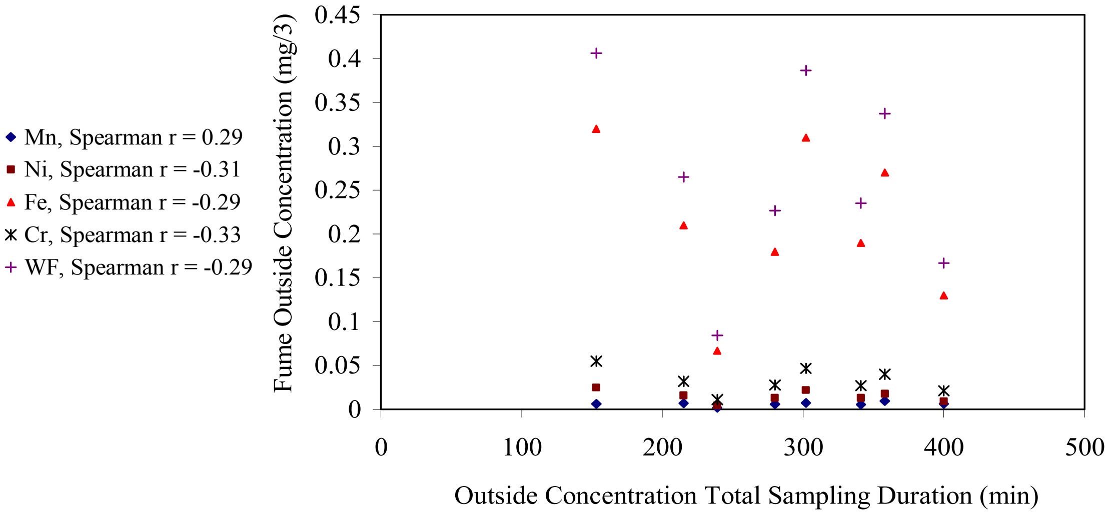

Figure 4. Comparison between Individual and Total Welding Fumes with Total Sampling Duration. No statistical significant correlation was found between metal fumes outside concentrations and sampling duration.

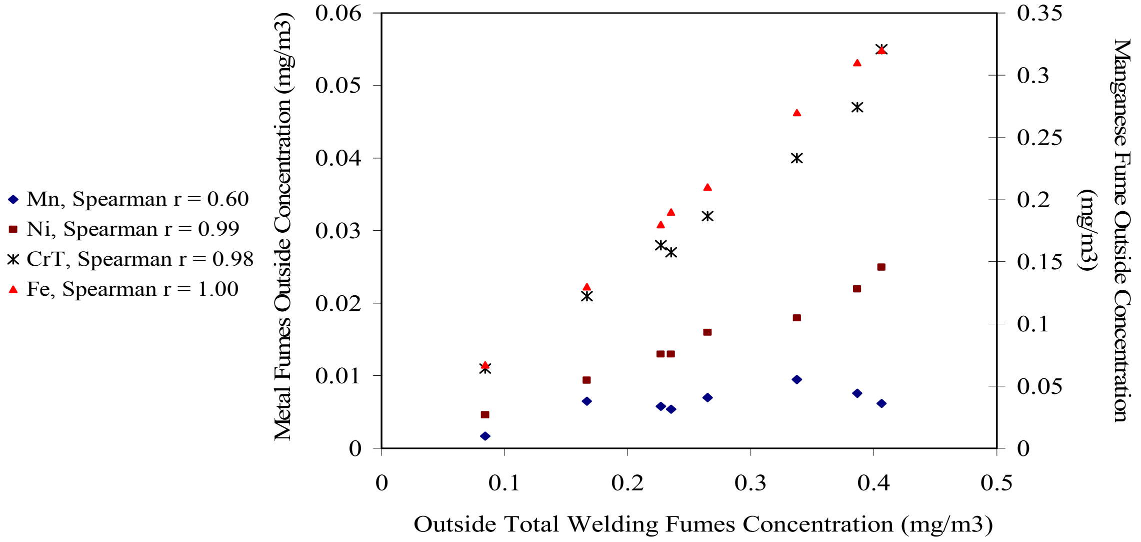

Figure 5. Comparison of Individual Welding Fumes with Total Welding Fumes Concentrations. A statistical significant correlation was found between nickel, iron, and total chromium when compared to total welding fumes.

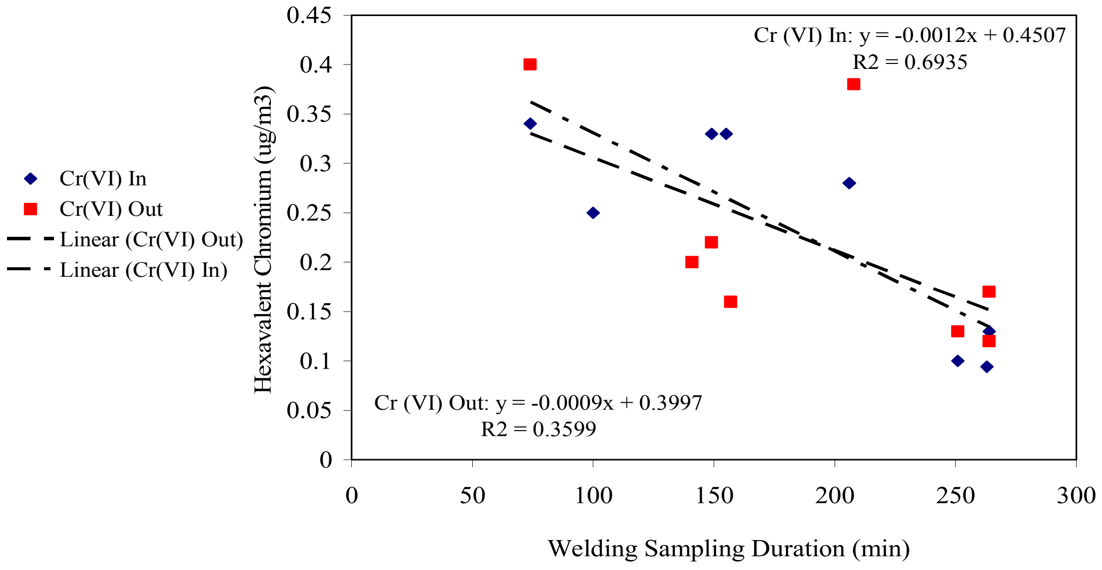

Figure 6. Hexavalent Chromium Inside and Outside Concentration Relationship Comparison with Sampling Time Duration. A weak linear correlation was found between outside of the welding helmet hexavalent chromium concentration and sampling duration, while a moderate linear correlation was found between inside of welding helmet concentration and sampling duration.

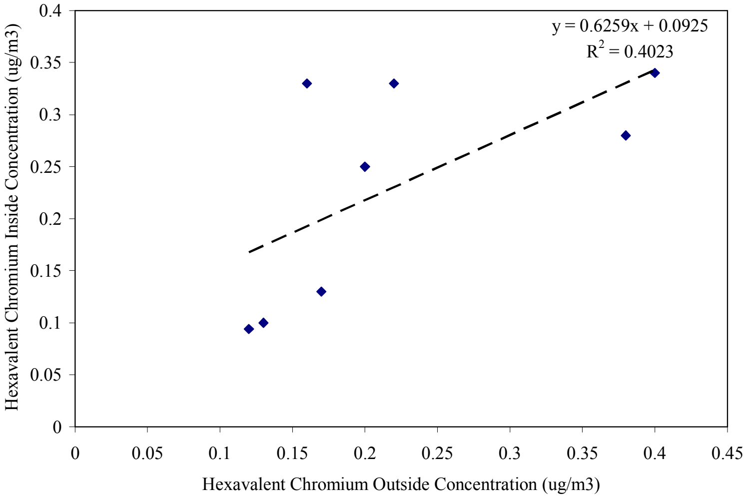

Figure 7. Hexavalent Chromium Inside and Outside Concentrations Linear Correlation. Cr (VI) inside and outside concentrations appear to have a weak linear correlation when compared with each other.

Hexavalent chromium concentrations did not linearly correlate with sampling duration or when comparing between inside and outside concentrations as shown in Figure 6 and Figure 7.

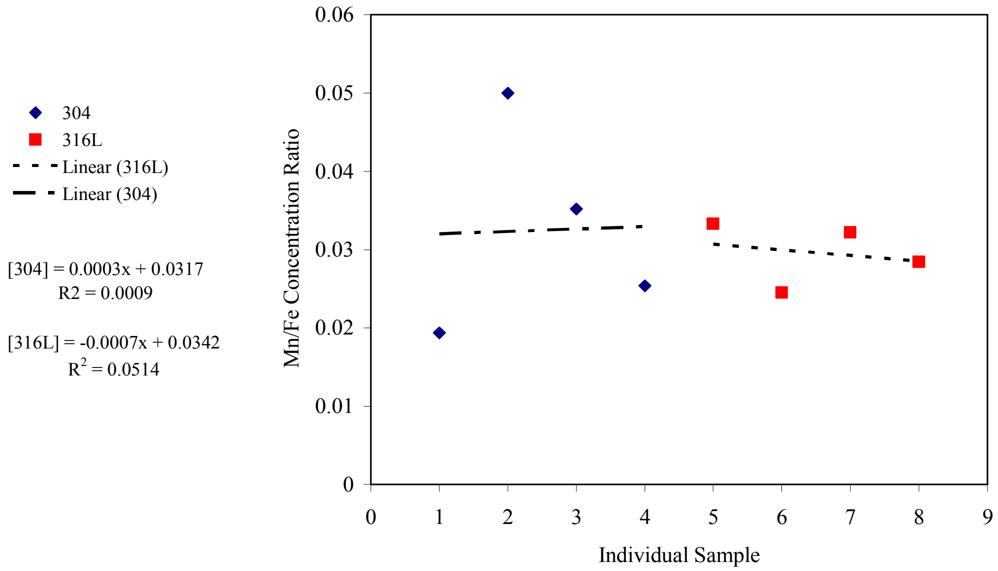

Figure 8. Manganese and Iron Oxide Outside Fume Concentration Ratio Compared to Sampled Employee. No linear correlation could be found between manganese to iron oxide fume welding ratio to employee ratio exposure.

Manganese to iron concentration ratios comparing 304 and 316L welding rods did not show a linear correlation between welding rods or among the individual samples as shown in

Figure 8. This analysis was performed in order to investigate manganese large concentration ratios when compared to other metal fumes.

Box plots of the inside to outside concentration ratios indicated larger concentration ratios for manganese and hexavalent chromium whether all samples were analyzed or samples below the LOD were removed as presented in Figure 16 and Figure 17.

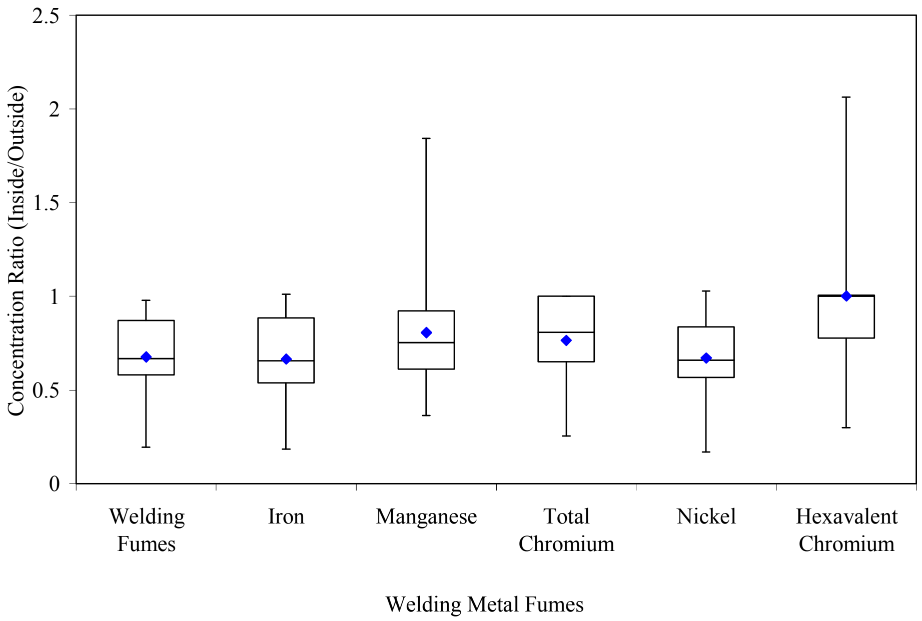

Figure 9. Ratio for Inside and Outside of the Welding Helmet Concentrations. Ratio for inside and outside of the welding helmet concentrations were plotted for hexavalent chromium with 15 paired samples and individual and total welding fumes with 12 paired samples. Greatest variation can be observed in manganese and hexavalent chromium concentration ratios.

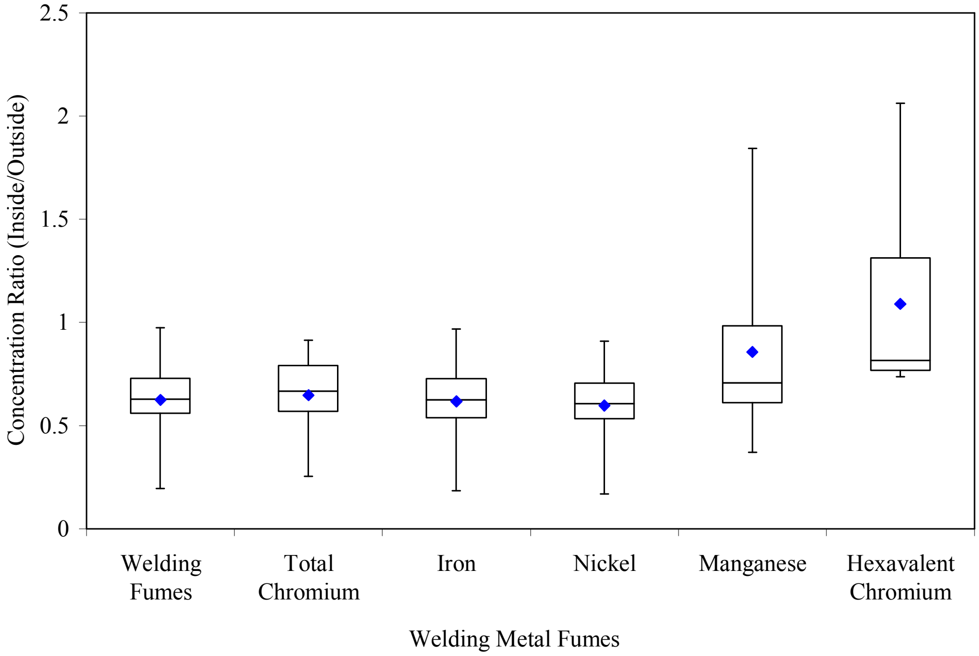

Figure 10. Ratio for Inside and Outside of the Welding Helmet Concentrations. Ratio for inside and outside of the welding helmet concentrations were plotted for hexavalent chromium with 8 paired samples and individual and total welding fumes with 8 paired samples. Greatest variation can be observed in manganese and hexavalent chromium concentration ratios.

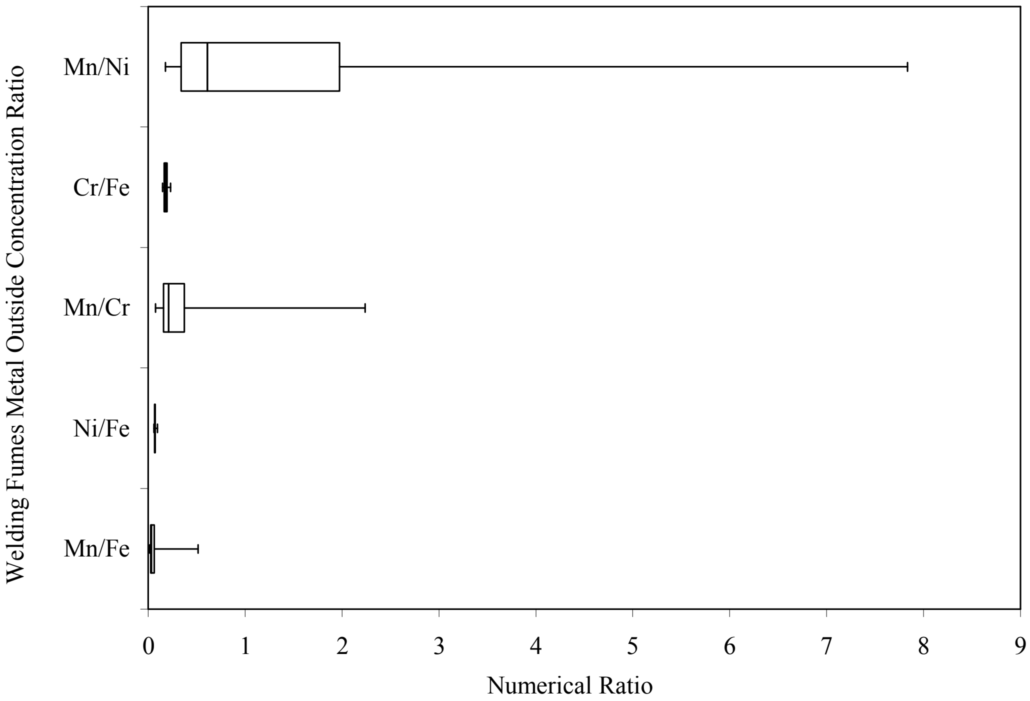

Figure 11. Welding Fumes Metal Fumes Concentration Comparison Ratio. Greatest variation in concentration ratios can be observed when manganese is compared to other metal fumes.

When all hexavalent chromium samples in the current study (n = 30) were taken into account for the analysis, four inside of the welding helmet samples were higher than outside even when the outlier was removed. When the hexavalent chromium samples below the LOD were removed (n = 12), three of the samples inside were higher than the outside of the welding helmet concentrations. None of the samples taken inside of the welding helmet were higher than the outside for total welding fumes and total chromium. For iron and nickel concentrations, when all samples (n = 24) were taken into account, one sample set for each was higher for the sample taken inside than the outside sample. For manganese concentrations, two samples inside of the welding helmet were higher than the outside concentrations. Inside and outside concentrations difference descriptive statistics are presented in Table 9 and Table 10.

Table 9. Inside and Outside Concentrations Difference Descriptive Statistics for Hexavalent Chromium Fumes.

| **Metal Fumes** | **n** | **Mean ($\mu g/m^3$)** | **Median ($\mu g/m^3$)** | **Standard Deviation ($\mu g/m^3$)** | **Variance $(\mu g/m^3)^2$** | **CI ($\mu g/m^3$)** | **Concentration Range ($\mu g/m^3$)** |
|---|---|---|---|---|---|---|---|
| Hexavalent Chromium | 9 | 10.9 | 0.06 | 32.6 | 1070 | 0.03-0.17 | 0.026 - 98 |
| Hexavalent Chromium (no outlier) | 8 | 0.0732 | 0.055 | 0.0498 | 0.00248 | 0.026-0.17 | 0.026 – 0.17 |

Table 10. Inside and Outside Concentrations Difference Descriptive Statistics for Welding Fumes.

| **Metal Fumes** | **n** | **Mean ($mg/m^3$)** | **Median ($mg/m^3$)** | **Standard Deviation ($mg/m^3$)** | **Variance $(mg/m^3)^2$** | **CI ($mg/m^3$)** | **Concentration Range ($mg/m^3$)** |
|---|---|---|---|---|---|---|---|
| Total Welding Fumes | 8 | 0.0745 | 0.0379 | 0.0952 | 0.00907 | 0.0206 – 0.128 | 0.0033 – 0.327 |
| Iron | 8 | 0.0832 | 0.0535 | 0.0852 | 0.00725 | 0.0242 – 0.142 | 0.01 – 0.261 |
| Total Chromium | 8 | 0.0122 | 0.008 | 0.0126 | 0.000159 | 0.00344 – 0.0209 | 0.0025 – 0.041 |
| Manganese | 8 | 0.00244 | 0.00205 | 0.00210 | $4.41 \times 10^{-6}$ | 0.000983 - 0.00389 | 0.0003 – 0.0064 |
| Nickel | 8 | 0.0064 | 0.00385 | 0.00639 | $4.09 \times 10^{-5}$ | 0.00197 – 0.0108 | 0.002 – 0.0208 |

Company 1 utilized 304 welding rods while Company 2 utilized 316L welding rods. These rod types contain higher nickel (316L) and chromium (304) content than manganese.

# DISCUSSION

In general, the means and medians for inside and outside concentrations of all metal fume species including total chromium, nickel, iron oxide, manganese, and total welding fumes did not exceed any occupational exposure limits such as the recommended exposure limits, permissible exposure limits, or threshold limit values. The only sample set that exceeded the PEL, REL and TLV was the outlier sample set for hexavalent chromium. The outlier which exhibited the highest exposure concentrations for hexavalent chromium was a sample set for a welder utilizing mechanical ventilation in the form of two fans that were placed opposite of each other. Also, this sample set had the lowest sampling duration at 58 minutes.

Possible explanations for the outlier sample set vary. Higher concentrations in shorter sampled exposures have been reported in other studies. Liu et al. (1995) suggested that in events of acute heavy exposures, the attenuation provided by the welding helmet may be protective, although highly variable. For low to moderate exposures, it was found in Liu et al. (1995) that samples taken outside of the welding helmet may be representative of actual exposure. Also, it was reported in Boelter et al. (2009) slightly higher concentrations for the total particulate and iron oxide fumes concentrations mean when sampling duration was short-term (15 minutes) than when compared to long-term (107 minutes) sample concentrations. For average total particulates, inside and outside of the welding helmet concentrations were 3.73 and 4.38 mg/m$^3$, respectively, when sampling duration was 15 minutes; and inside and outside of the welding helmet concentrations of 2.89 and 3.03 mg/m$^3$, respectively when long-term personal (107 minutes) samples were taken (Boelter et al., 2009). Factors such as LEV or mechanical ventilation, welder’s technique, skill, and body posture, and fumes’ aerodynamics may play a role on these events were shorter sampling duration exhibit higher fume concentrations.

The welder who exhibited the hexavalent chromium concentration outlier set was sampled for welding fumes. The welding fumes sample set results was not unusually high when compared to other sample sets. Sampling conditions varied in regards that only one fan was utilized when sampling for welding fumes instead of the two fans opposite of each other when the hexavalent chromium sample set was being sampled.

For hexavalent chromium, both the mean and median were higher for inside concentrations sample than outside concentrations even when the outlier was removed from the statistical analysis. The hexavalent chromium mean and standard deviation inside and outside of the welding helmet without the outlier were close in numerical values as shown in Table 1 and Table 7. The hexavalent chromium variance differed by over 10 times when the outlier was included in the analysis, but was similar in value when the outlier was removed as shown in Table 3 and Table 8.

The mean and median concentrations were higher for outside of the welding helmet concentrations than inside concentrations for total welding fumes and the individual metal fumes. Differences between inside and outside concentrations were up to five times different for all sample sets when compared between each other. The manganese means, standard deviations, medians, and variances were close in numerical value when comparing inside and outside of the welding helmet concentrations. The largest concentrations range can be seen in hexavalent chromium and manganese sample sets as shown in Table 3, Table 4, and Table 8. Large mean differences were also reported in Chung et al. (1999) for welding fume concentrations among an area sampler, personal sampler, and mannequin samples when compared to each other.

In terms of helmet attenuation, a great variation was seen among different sample sets. A reduction of up to 80% was found between inside and outside concentrations for all sample sets, when outside concentrations were greater than inside concentrations. The least attenuation provided was for hexavalent chromium with up to 26% concentration reduction when the outlier was removed.

Statistically significant differences between inside and outside concentrations were found for total welding fumes, nickel, iron, and total chromium, where outside of the welding helmet concentrations were greater than inside concentrations. For manganese and hexavalent chromium, no statistically significant difference was found between inside and outside concentrations. This finding is consistent with Flynn and Susi (2009), where no significant difference was found between manganese concentrations in unpaired samples inside and outside of the welding helmet. The authors discussed the conflict presented in this finding, also stating how the face shield is acting more appropriately as an engineering control rather than a NIOSH approved respiratory device. The authors even suggested that OSHA revise the existing policy of sampling location.

The non-statistical significant difference between the inside and outside of the welding helmet concentration of manganese and hexavalent chromium concentrations may be attributed to the small metal content in welding rods and large concentration range. Manganese comprised the smallest amount in the welding rod filler material metal content utilized in this study and hexavalent chromium is a fraction of the total chromium concentration. It can be assumed that both of these fumes comprised of the lowest amount in the fumes composition and, therefore, generation. Manganese concentration variance was minimal when comparing inside and outside concentrations as well as the means and the standard deviations. Hexavalent chromium variance, mean, and standard deviation were also minimal when comparing inside and outside concentrations without the outlier. When the outlier was included, the variance was ten times different when comparing inside and outside concentrations. Particle size distribution may have also attributed to the non-statistically significance found for manganese and hexavalent chromium. Liden and Surakka (2009) reported manganese particle size of less than 2 micrometers.

Also, manganese and hexavalent chromium samples exhibited the greatest variation in inside and outside concentration ratios. Lower concentration differences (between inside and outside concentrations) exhibited the higher concentration ratios. Ratios greater than one indicate inside concentrations greater than outside concentrations. Inside of the welding helmet concentrations greater than outside concentrations were investigated. It was observed that welders with samples inside greater than outside concentrations used fans and a powered air-purifier respirator. This may have affected the aerodynamics of the welding fume plume.

Iron oxide fumes had the largest welding fumes content. When the concentrations were transformed to a time-weighted average, all metals correlated with each other with the exception of manganese with nickel (Appendix C. Figure 12). It can be assumed that welding fumes prediction based on correlation models are possible. However, Chung et al. (1999) noticed that when welding fumes were calculated from the manufacturer's data sheet, welding fumes concentrations tended to be underestimated. Therefore, estimating welding fumes from the manufacturer's data sheet or prediction model should be exerted with caution. More detailed, specific, and reliable models should be developed in order to predict welding fumes from models.

Factors that likely influenced exposure in this study, but were not quantified included the use of mechanical ventilation, general dilution ventilation, and local exhaust ventilation. Fans were used and bay doors were opened intermittently during sampling. Welders also performed grinding, cutting, and polishing that may have affected their exposure concentrations. The welding helmets were always worn while performing welding tasks, but was quickly removed and placed in the upward position as soon as the welding was done to verify the weld and to position the next material to weld.

Metal fume oxides chemical reactions were not accounted for when welding fumes were sampled. Fume aerodynamics and worker body position may have reduced helmet attenuation. Processes such as agglomeration were not studied in detail, or investigating assumptions such as homogenous conditions inside of the welding helmet and heterogeneous conditions outside of the welding helmet. Wallace et al. (2001) also accounted for factors such as wind effect and welder position to have affected ventilation evaluation results and exposure. Factors that may affect exposure concentrations also include welding type, base metal, industry, electrode, power configuration, arc time, flux utilized, welding current, welding voltage, welding space enclosure, body posture, work speed, amount of welders in work stations, welding duration, welding experience, LEV presence and proper use, and welder’s technique and skill (Burgess, 1995; Harris, 2002; Stern et al., 1986; Yoon et al., 2003). Fume generation rate may be impacted by the current density or amperage per cross section area of the electrode. Eating lunch and drinking mugs present at the work station may also affect worker’s exposure through ingestion.

Ventilation conditions varied among sampling events. Although all of the welding areas sampled had ventilation systems, ventilation varied among welding areas within the companies. Company 1 had two main welding areas. In one of the areas, LEV was utilized; the other welding area in Company 1 utilized fans. Welders that utilized fans only used one, except for one welder, which utilized two fans. This welder utilized the two fans when the hexavalent chromium sample set was being collected, but used one fan when the welding fumes sample set was being collected. For this hexavalent chromium sample set, the outlier was measured. Company 2 had one assigned welding area, but welding tasks were also performed at another location within the company where welding tasks needed to be completed. General dilution ventilation was present at both sites within Company 2. At both companies, bay doors were opened and closed intermittently. LEV use was not compared between companies due to lack of consistency among welding sampling durations, different welding rods utilized, and lack of paired samples in welders using LEV and when no LEV was present. Awareness of LEV function and effectiveness was unclear among welders when asked about specific information or training.

In general, it was expected to observe higher concentrations outside of the welding helmet than inside of the welding helmet as it was shown in the data. When inside of the welding helmet concentrations were higher than outside, it is believed that mechanical ventilations or fans as well as the powered air-purifier respirator affected the measurement. Mixed results were found for mean difference concentrations. Although most of the mean differences in concentrations were statistically significant, this was not true for manganese and hexavalent chromium. Factors such as lower metal content in welding rod, lower concentration fraction, and particle size distribution may have contributed to this finding.

## Research Limitations

Many factors affect welding fumes, and it is challenging to control for all variables in a field study rather than in an experimental or controlled setting. Finding companies that would agree to the study conditions were scarce. When a company agreed to the study conditions, it was difficult to coordinate sampling days that would allow for sampling for more than one hour. Other factors not controlled in this study include the placement location inside the welding helmet whether the placement was left or right of the helmet or outside in the collar region. One of the welders sampled was wearing a powered air-purifying respirator. The use of ventilation varied among welders and companies as well as the welding rods utilized as filler materials, although both were stainless steel. Some samples had to be discarded from the statistical analysis because values were below the LOD. Total welding fumes was assumed to be the addition of the individual metal fumes concentrations. Variables such as arc time or voltage were not documented. Also, sample size was limited due to funding limitations.

# CONCLUSION

Paired samples were collected for inside and outside of the welding helmet comparison. While some metal fumes resulted in significant differences between inside and outside of the welding helmet such as welding fumes, nickel, iron, and total chromium, others did not, such as manganese and hexavalent chromium. Also, great variation among metal fumes concentration was exhibited among sample sets.

Given the results of this study, it is challenging to recommend a definite sampler location for welding sampling for several reasons. First, welding fume generation and welding fume content is directly influenced by the type of welding process performed. Second, other factors such as base metal and welding rod material greatly affect fume content as well. Work practices can greatly affect fume exposure as fume generally persist in air and direct exposure may occur when a welder places the welding helmet in the upward position immediately after finishing the weld.

Based on the results of this study, it is suggested that monitoring assessment be done outside of the welding helmet, or that a new head mounted filter design is developed for this specific monitoring that can better assess welding fume exposure such as the one utilized in Chung et al. (1999). The sample placement in the developed headset mount was able to maintain the same filter sampling location even if the welding helmet is removed or raised.

It is also crucial for welders to receive safety and health training in regards to welding health hazards and proper ventilation use. As the literature indicated, welders may not be aware of health hazards or the available engineering controls. It needs to be emphasized that welders should not be in the path of the fume.

This study was performed to assess the current monitoring location and exposure for welding fumes. Although the welding helmet attenuates welding fumes, it can be determined that assessing welding fumes inside of the welding helmet can lead to questionable results. The main purpose of the welding helmet is to protect welders from the ultraviolet radiation generated by the welding arc. Therefore, vision is impaired when utilizing the welding helmet as it permits to only see the arc due to the dark shade. For this reason, welders often removed their welding helmet to verify the weld. With the removal of the welding helmet, any attenuation expected is lost and direct exposure occurs if no other methods are used, for example, the proper use of LEV and respiratory protection. Welders in this study commented on daily expulsion of black mucus as a normal occurrence. Even if welding fumes and its specific metal constituents did not exceed OEL’s in most sampling events, it would be advisable to have welders participate in respiratory monitoring and observe future pulmonary function.

## Recommendations

In general, several recommendations can be suggested to employers and individuals that perform welding tasks:

- ✓ Sampling location outside will most likely capture worst case scenario for fumes exposure assessment. Since fumes are not expected to settle immediately after generation, exposure may occur if the helmet is placed in the upward position and if welder verifies the weld by nearing his/her personal breathing zone into the fume plume.
- ✓ Local exhaust ventilation (LEV) is crucial when minimizing welding fumes exposure. If properly used, it has been shown to significantly reduced exposure concentrations when

welding. When LEV is available, training should be provided in order to explain LEV proper use and to inform welders.

- ✓ Health and safety training, specifically on welding safety and adverse health effects due to overexposure to welding fumes should be provided to employees by employers. Alternatives to minimizing exposure such as welding technique and skill including not being in the path of the plume should be emphasized.
- ✓ Respiratory protection is encouraged. Additional to welding fumes, welders may be exposed to grinding and spatter particles. Respiratory protection may required face mask or respirator fit test, training, and maintenance.
- ✓ The use of an improved helmet, whether it has a removable face shield with darken screen or a welding helmet where the screen automatically darkens when the arc is detected is recommended. Correct use of these helmet features, especially keeping the helmet worn at all times when welding is performed would reduce welder's exposure to welding fumes.
- ✓ Monitoring should be performed, if work load increases or if operation or work station is changed. Individual metals can cause lung irritation, respiratory tract infections, dermatitis, and other adverse health effects.
- ✓ It is recommended to perform annual pulmonary function test. The test will allow early detection of changes, such as a decrease in lung function due to asthma or smoking.
- ✓ For industrial hygienist monitoring welding fumes, a modified sampling location in the helmet would allow for better assessment. Developed models allow sampling location to remain close to the nose and mouth area even if helmet is place in upward position.

## Future Work

For future welding sampling location comparison studies, it is best to conduct sampling collection in a controlled setting. In order to investigate inside and outside of the welding helmet concentrations comparison, it is best to control for variables such as welding rods filler material as well as welding process, consistent sampling durations, similar welding station conditions among welders sampled, LEV conditions, and consistent use of respiratory protection or absence of it. LEV comparisons would have been possible if similar conditions would have been maintained when comparing the use of LEV with samples where LEV was not utilized.

It is of interest to investigate exposure when helmet is in the upward position and when the helmet is not removed. Investigating if the helmet in the upward position affects significantly the exposure concentration would support helmet and sampling location modification recommendations. Biological monitoring in welder’s bodily fluids would allow better assessment of the metabolized exposure concentrations of welders to welding fumes.

Also, studying total particulate matter and fumes background in welder’s work stations can improve welder’s exposure assessment. Studies in particle size distribution and prediction models, such as the models developed by Hobson et al. (2011) can also be used to estimate welder’s exposure concentrations and to better assess potential adverse health effects depending on the welding process utilized among others.

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# APPENDIX A

## Laboratory Analysis Information

The Wisconsin Occupational Health Laboratory (WOHL) analyzed hexavalent chromium and welding fumes collected samples. Blanks were taken at the day of sampling. Up to three blanks were taken depending on the number of samples collected in a sampling day.

Table 11. WOHL Laboratory Analysis Information

| **Parameter** | **Hexavalent Chromium** | **Welding Fumes** |
|---|---|---|
| Analyte | Hexavalent Chromium | Welding Fumes-Metals Only |
| Media Catalog Number | 86 | 14 |
| Reference Method | OSHA ID-215 (IC) | NIOSH 7303 (ICP) |
| Flow Rate | 2 L/min | 2 L/min |
| Media Name | Hexavalent Chrome filter, unweighed PVC, 37 mm, 5.0 micron, 2 piece, labeled Na/K/Cr6, clear band | MCE filter, 37 mm, 0.8 micron, 3 piece, labeled AA, white band |
| SAE | 0.116 | 0.184 |

Table 12. WOHL Reporting Limit For Welding Fume Metals

| **Metal Fume** | **Reporting Limit (ng/sample)** |
|---|---|
| Hexavalent Chromium | 50 |
| Aluminum Welding Fumes (as Al) | 10 |
| Boron | 1.5 |
| Barium | 0.15 |
| Cadmium Fume(as Cd) | 250 |
| Chromium, Metal & Insol | 4.0 |
| Cobalt, Metal, Fume, Dust | 0.25 |
| Copper Fume (as Cu) | 1.25 |
| Iron Oxide Fume | 7.0 |
| Lead, Inorganic Fume & Dust | 1.8 |
| Magnesium Oxide Fume | 8.3 |
| Manganese Fume (as Mn) | 0.25 |
| Molybdenum (Insolubles) | 0.50 |
| Nickel | 1.0 |
| Zinc Oxide Fume | 2.2 |

# APPENDIX B

## Metal Fume to Metal Fume Correlation Figures

It is shown in the correlation among metals figures below that most metals correlated among each other, but this was not the case for manganese.

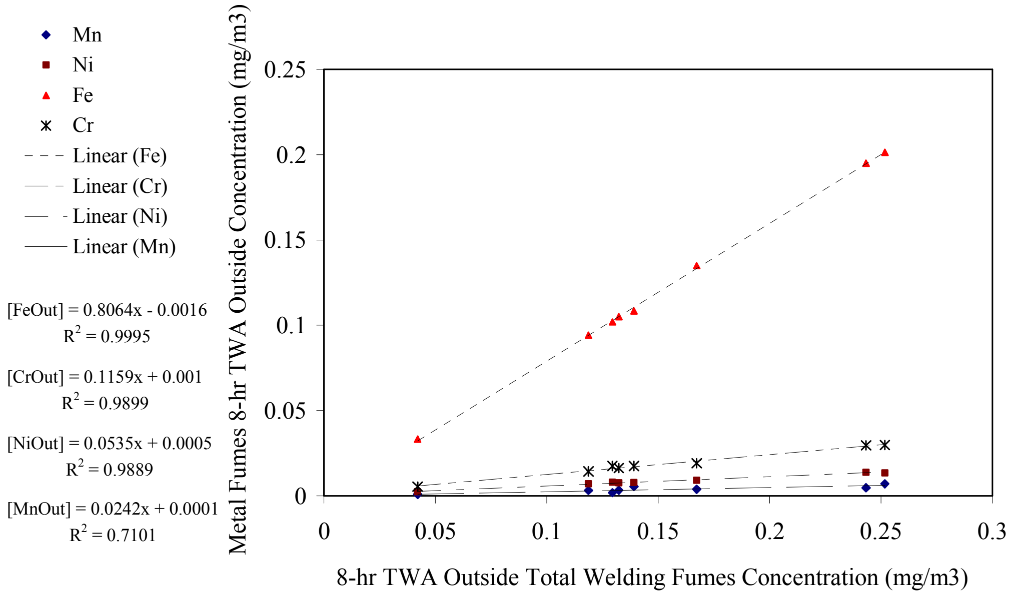

Figure 12. Adjusted 8-hour Time-Weighted Average Individual Metal Fumes Compared with Total Welding Fumes Outside Welding Fumes. A stronger correlation can be inferred for iron oxide fumes and total welding fumes, but sampling time was adjusted for 8 hours. Iron is the metal with highest composition in welding rods.

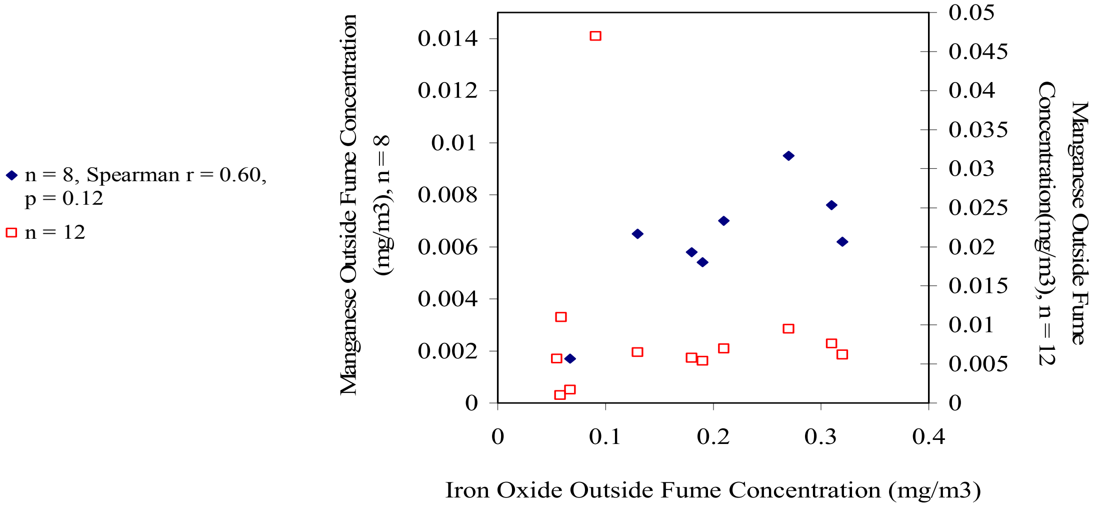

Figure 13. Correlation Comparison between Manganese and Iron Oxide Outside Fumes Concentration. No statistical significant correlation could be found between manganese and iron concentrations sampled outside of the welding helmet.

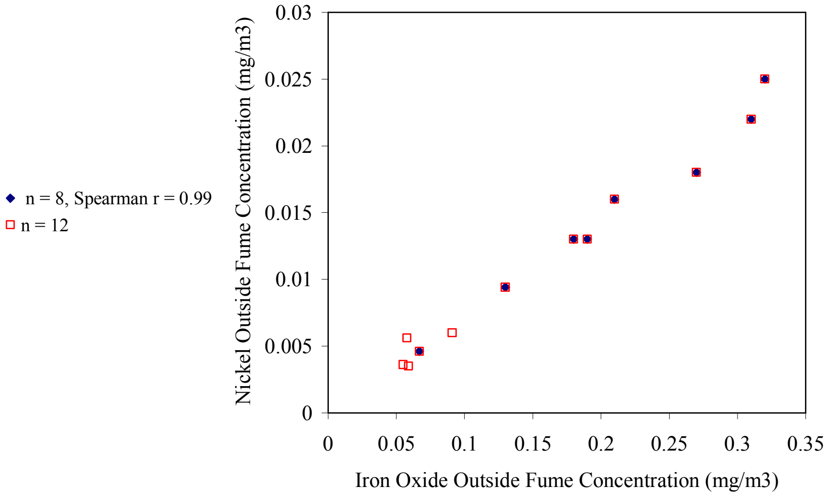

Figure 14. Correlation Comparison between Nickel and Iron Oxide Outside Fumes Concentration. A statistical significant correlation was found between nickel and iron concentrations sampled outside of the welding helmet.

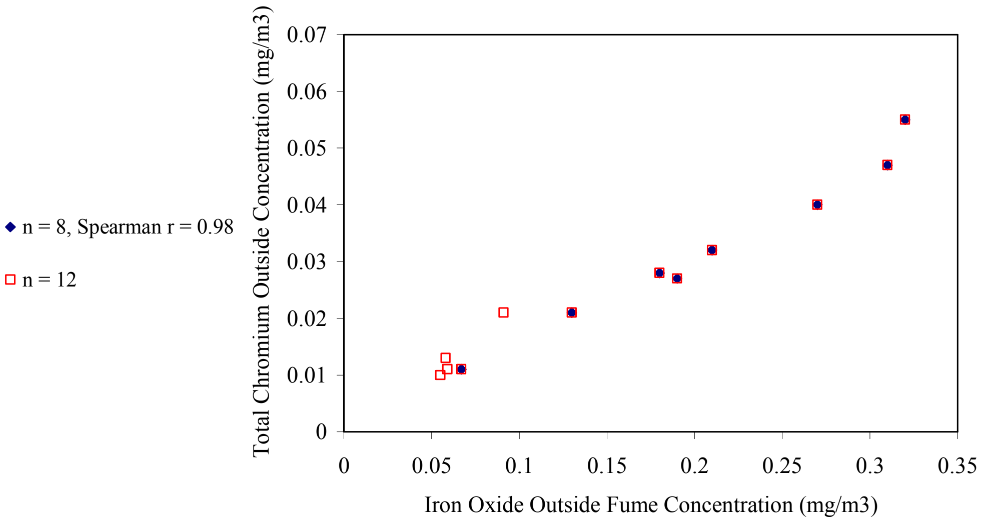

Figure 15. Correlation Comparison between Total Chromium and Iron Oxide Outside Fumes Concentration. A statistical significant correlation could be found between total chromium and iron concentrations sampled outside of the welding helmet.

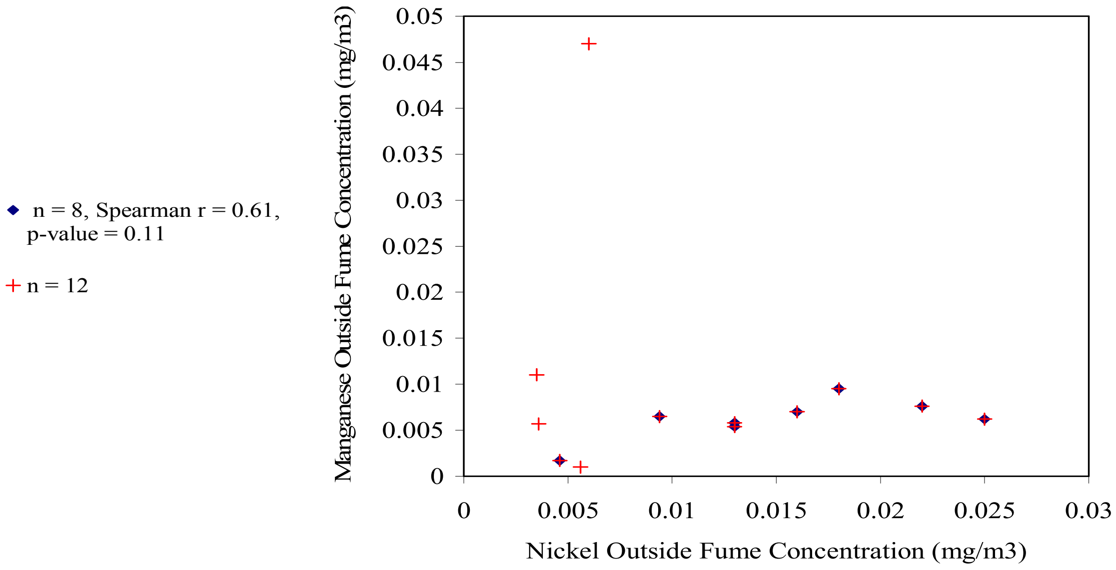

Figure 16. Correlation Comparison between Nickel and Manganese Outside Fumes Concentration. No statistical significant correlation could be found between nickel and manganese concentrations sampled outside of the welding helmet.

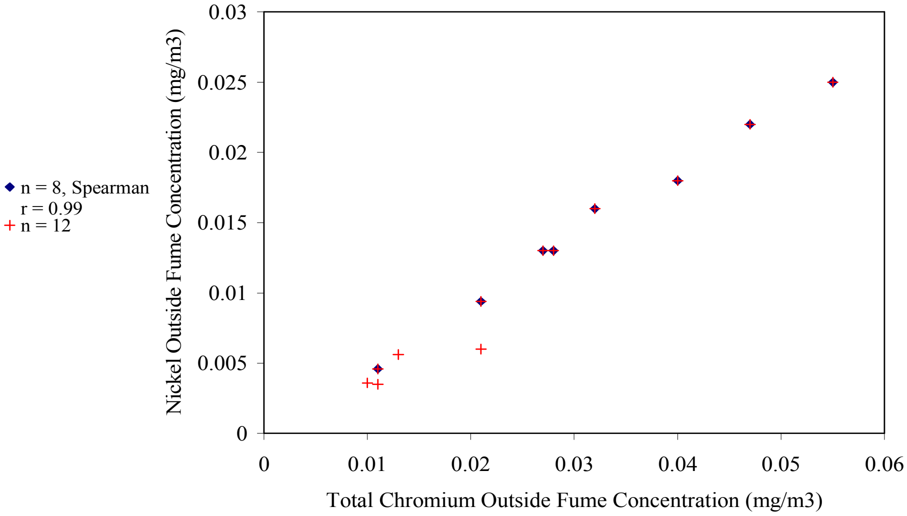

Figure 17. Correlation Comparison between Total Chromium and Nickel Outside Fumes Concentrations. A statistical significant correlation was found between total chromium and nickel concentrations sampled outside of the welding helmet.

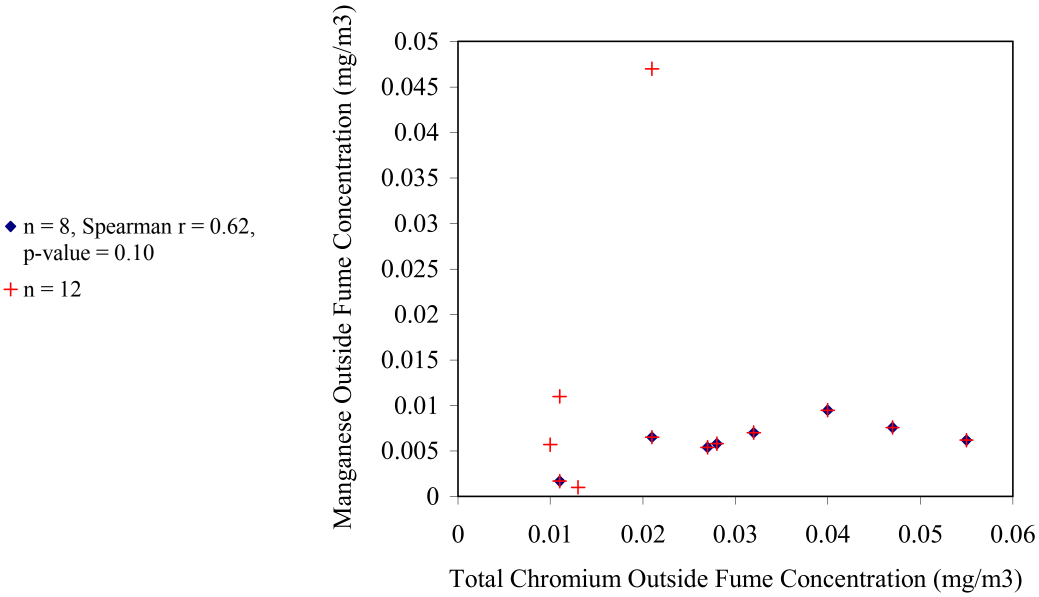

Figure 18. Correlation Comparison between Total Chromium and Manganese Outside Fumes Concentration. No statistical significant correlation could be found between total chromium and manganese concentrations sampled outside of the welding helmet.

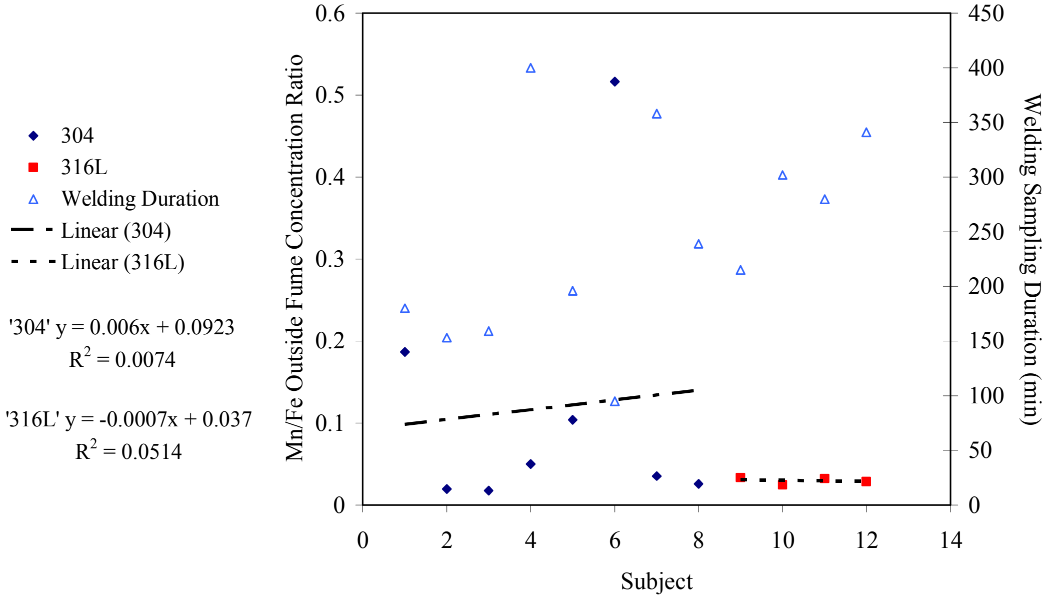

Figure 19. Manganese and Iron Oxide Outside Fume Concentration Ratio Compared to Sampled Subject (or Employee) and Welding Duration. No linear correlation could be found between sampling duration and manganese to iron oxide fume ratio, or between welding rod used.

# LIST OF ABBREVIATIONS

$\alpha$ = alpha

ACGIH - American Conference of Governmental Industrial Hygienists

AIHA – American Industrial Hygiene Association

ANSI – American National Standards Institute

ASTM – American Society for Testing and Materials

AWS – American Welding Society

CEN –European Committee for Standarization

CFR – Code of Federal Regulation

CI – Confidence Interval

Cr (VI) – Hexavalent Chromium

CrT – Total Chromium Fumes Concentration

CPWR - Center for Construction Research and Training

EHD – Elastohydrodynamic Metals Method 400.2 rev.3

EPA- U.S. Environmental Protection Agency

Fe – Iron Oxide Fumes Concentration

FCAW - Flux-Cored Arc Welding

GTAW – Gas Tungsten Arc Welding

IARC – International Agency for Research on Cancer

ICP – OES – Inductively Coupled Plasma Optical Emission Spectrometer

IRB – Institutional Review Board

LEV – Local Exhaust Ventilation

LOD – Limit of Detection

MIG – Metal Inert Gas

MMAW – Manual Metal Arc Welding

Mn – Manganese Fumes Concentration

MSA – Mine Safety Appliances Company

N/A – Not Applicable

NMAM – NIOSH Analytical Method

Ni – Nickel Fumes Concentration

NIOSH – National Institute for Occupational Safety and Health

NTP – National Toxicology Program

OEL - Occupational Exposure Limits

OSHA - Occupational Safety and Health Administration

PAPR – Powered Air-Purifier Respirator

PAW – Plasma Arc Welding

PEL - Permissible Exposure Limit

REL - Recommended Exposure Limit

SMAW – Shielded Metal Arc Welding

TIG – Tungsten Inert Gas

TLV – Threshold Limit Value

TWA – Time-Weighted Average

TWI – The Welding Institute

UV – Ultra-Violet

WOHL – Wisconsin Occupational Health Laboratory