Manganese and Health in the Welding Environment

by

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B.S., Welding Engineering, The Ohio State University, 1997
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Submitted to the Department of Materials Science and Engineering
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ABSTRACT

There are approximately 0.5 million full-time welders in the U.S., with even more workers welding intermittently. Over the past thirty years there has been increased interest in the effects of welding fume on the health of these workers. Manganese is an essential element in the making of all steel products and steel welding electrodes and is, therefore, present in fume that is generated during welding of these materials.

Manganese is essential to humans in small amounts, but in larger amounts it is a neurotoxin and causes manganism, a disease with symptoms similar to Parkinson's disease. Manganese has been reported to cause adverse health effects in industries such as paint production, battery production, and manganese ore mining. Occupational exposure limits for manganese have been developed based on these industries, and the lowest limit, the TLV® established by the American Conference of Governmental Industrial Hygienists, is a source of concern to the welding industry.

This thesis attempts to answer the question, "Is the current exposure limit for manganese feasible and does it make sense for the welding industry?" It does this by evaluating whether there is evidence of manganese harm to welders, and evaluating the issues associated with this topic.

Calculations show that during an eight-hour shift at current acceptable standards, it is not possible for a welder to ingest enough manganese from the welding environment to cause manganism. There is also evidence that welding fume, which contains iron as well as manganese, carries its own antidote to manganism. A hypothesis suggests that manganese in welding fume, due to affects associated with iron, may not be transferred in harmful amounts across the blood-brain-barrier (BBB). Economic costs to industry would be substantial in meeting the lower exposure limit.

The evidence suggests that, at the current permissible level of exposure to total welding fume, the risk of a welder contracting manganism is essentially zero and the economic costs that would be involved with the lower TLV® are not justified.

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To my true sources of inspiration and happiness,
my wife, Allison,
and my sons, Benjamin and Luke.

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PUBLICATIONS

Research Publications

1. Balmforth, M. C. and Lippold, J. C. 1998. A preliminary ferritic-martensitic stainless steel constitution diagram. *Welding Journal*, 77(1): 1-s to 7-s.

2. Balmforth, M. C. and Lippold, J. C. 2000. A new ferritic-martensitic stainless steel constitution diagram. *Welding Journal*, 79(12): 339-s to 345-s.

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CHAPTER 1

INTRODUCTION

Over the past thirty years, since Congress passed the Occupational Safety and Health Act in 1970, there has been an increased interest in industrial safety and occupational hygiene. As science has improved, so has the ability to understand the toxicity of chemical substances, and occupational exposure limits have been set or proposed for many of these substances.

The United States Bureau of Labor Statistics (BLS) reports that there are nearly 0.5 million workers who perform welding and cutting operations full-time in the U.S. (Ref. 1). There are also many other workers who weld intermittently. For at least twenty years, there has been growing interest over the health effects of welding fume on these workers, due to the existence of potentially toxic metals in the fume. Although it is well known that iron oxide, the main constituent in steel welding fume, is nontoxic (Ref. 2), steels contain other alloying elements that, in their pure forms (as used in other industries) have been found to have serious health consequences. All welding fume contains manganese, and fume from the welding of stainless steels contains chromium and nickel. Manganese has been recognized as a neurotoxin in large doses, causing manganism, a disease with symptoms similar to Parkinson's disease, and chromium and nickel have been shown to be carcinogenic. Welding fume has attracted attention after the adverse effects of these elements were reported in other industries, and there has been increasing interest in determining whether these elements, as present in welding fume, pose any health threat to welders. The question of whether the exposure limits that were established using data from other industries should apply to welding fume has also been raised.

The regulation of toxic substances is important in maintaining the health of workers throughout industry. Government agencies, such as the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) have been established to aid in the protection of worker health. These agencies, along with the private American Conference of Governmental Industrial Hygienists (ACGIH), have set exposure limits for chemical substances in the workplace. It is the obligation of industry to meet these exposure limits. Recently, exposure limits for manganese, chromium and nickel have been reduced. Because these regulations affect American industry, there are societal, health, and economic impacts to be considered.

In this thesis, the issues surrounding manganese and health in the welding environment are discussed. General hazards in the welding environment are considered, followed by a thorough description of manganese, including its applications and effect on human health. Welding fume and the variables that effect worker exposure are discussed. The subsequent section includes a description of the regulating agencies, along with their individual exposure limits for total welding fume and manganese fume. One of the central objectives of this thesis is to answer the question, "Is the proposed exposure limit for manganese reasonable and does it make sense for the welding industry?" This question is addressed by examining the issues surrounding manganese in welding fume, including its oxidation state and the amounts that are typically found in welding fume. Calculations are performed to determine if welders can be exposed to enough manganese to cause manganism, and a possible biological mechanism that suggests manganese in combination with iron might not be as harmful as manganese alone is presented. Other general issues that must be considered in determining exposure limits for manganese in welding fume are also discussed. Finally, costs and methods for compliance with the exposure limits will be presented.

The information presented here will lead to a greater understanding of manganese in welding fume and its effect on workers. As this understanding is enhanced, reasonable occupational exposure limits, which prevent excessive regulation while at the same time ensuring and maintaining a safe working environment, will be able to be promulgated. This will be a benefit to industry, in that undue costs of compliance will be avoided. Workers will benefit by having the reassurance of working in a safe environment, and society as a whole will be improved through increased productivity, safety, and economy.

CHAPTER 2

BACKGROUND

2.1 Welding and Health

The effects of welding and brazing on health come from chemical, physical, and radiation hazards. Common chemical hazards include particulates (lead, nickel, zinc, iron oxide, copper, cadmium, fluorides, manganese, chromium) and gases (carbon monoxide, oxides of nitrogen, ozone). Each of these can create adverse effects when ingested by the human body if delivered in the appropriate dose and chemical state. Physical hazards related to welding include electrical energy, thermal energy, noise and vibration. Electromagnetic radiation occurs in the visible, ultraviolet, and infrared frequencies. As an example, ultraviolet light produced by the electric arc welding process causes almost all welders to experience an acute photo kerato conjunctivitis, or "arc-eye," on one or more occasions during their career. Epidemiological studies of welder populations have demonstrated that welders are at greater risk for respiratory illness. Reported affects range from airway irritation, acute metal fume fever, acute chemical pneumonitis and chronic bronchitis to lung function changes. They also appear to have a higher risk of lung cancer, but the cause is uncertain due to confounding variables such as tobacco use and asbestos exposure. The aerosols, gases and particulates comprising welding fume are considered to be among the more harmful of the many exposures to welders (Ref. 3).

Since the 1800s, it has been known that ingestion of huge quantities of nearly pure manganese oxide particulates can cause neurological disorders. In 1989, Rekus (Ref. 4) warned the welding industry to recognize the toxicity of certain elements in welding fume and he listed manganese as one of the toxic elements that could affect the nervous system. The composition of welding fume is dependent on the welding process being used. Processes for welding steel utilizing both bare (e.g. GMAW) and coated (e.g. SMAW) electrodes have the potential to produce fumes containing some concentration of manganese.

2.2 Manganese

When a welder performs his craft on most steels, including mild and stainless steels, he is potentially exposed to manganese. Manganese can be found in at least trace amounts in all steels and the filler metals used to weld these steels because it is essential to the steel making process. The fumes that are produced during welding of these materials contain manganese in varying amounts, depending on the composition of the base metal and filler material, the welding process being employed, and a variety of other factors.

Manganese is a grayish-white metallic element that resembles iron in many ways. It has an atomic weight of 54.9, a melting point of 1245°C (2268°F) and a boiling point of 2150°C (3902°F). Manganese exists in different allotropic crystalline forms depending on the temperature. From room temperature to 710°C (1310°F) the crystalline form is simple cubic, and it is designated as alpha manganese. Heating above this temperature will produce other cubic and tetragonal forms, until the delta form (face-centered cubic) melts. Manganese exists in five valence states, which are listed in Table 2.1.

Table 2.1. Manganese valence states.

Valence	**Nomenclature**
+2	manganous
+3	mangonic
+4	manganite
+6	manganate
+7	permanganate

Manganese is an abundant element, comprising about 0.1 % of the earth's crust (Ref. 5). It does not occur naturally in the metallic state, but is a component of over 100 minerals, including various sulfides, oxides, carbonates, silicates, phosphates and borates. The most commonly occurring manganese-bearing minerals include pyrolusite (manganese dioxide), rhodochrosite (manganese carbonate) and rhodanate (manganese silicate) (Ref. 6).

2.2.1 Effects on Human Health

In trace quantities, manganese is an essential element; Hine (Ref. 7) stated the human requirement for manganese is three to nine milligrams per day, with the liver, pancreas, and bone containing the highest concentrations. There is conclusive evidence from studies in humans that inhalation exposure to high levels of manganese compounds (usually MnO_2, but also including other compounds of Mn^{+2} and Mn^{+3}) can lead to a disabling syndrome of neurological effects termed "manganism". Manganism occurs because too much manganese injures a part of the brain that helps control body movements (Ref. 6).

Early symptoms of chronic manganism include restlessness, irritability, and a tendency to cry or laugh without purpose. These symptoms may be followed by apathy, visual hallucinations, uncontrollable impulses, flight of ideas, mental confusion, or euphoria. Mask-like facial expression, spastic grin, muscle rigidity, slow gait with sliding of the feet, increased and abnormal reflexes, monotonous blurred speech with poor articulation, irregular handwriting, impaired hearing, double vision, abnormal reactions to pain, touch, heat, and pressure, excessive salivation and perspiration, sexual impotence and diminution of libido have been described by various authors (Refs. 8, 9, 10).

In manganism, mental activity is reported to be slowed, judgment impaired, and memory weakened, but intelligence remains normal. There is usually a low white blood cell count and increased levels of manganese in the blood, urine, hair, and fingernails. Some illnesses that may be mistaken for manganism include Parkinson's disease, multiple sclerosis, paralysis agitans, advanced syphilis, Wilson's disease (progressive lenticular degeneration associated with liver degeneration), and epidemic encephalitis (Ref. 10).

These effects are largely irreversible, except in very mild cases, and some recovery may occur when exposure to manganese ceases. The neurological disturbances may progress to partial or total disability (Ref. 8).

To date, manganism has been documented only in workers exposed to high levels of manganese dust or fumes in mines or foundries. According to Public Health Bulletin 247 (Refs. 10, 11), the lowest average concentration at which a case of chronic manganism was found was 30 mg/m^3, while some cases required up to 90 mg/m^3. A human typically breathes about 10 m^3 of air per day (Ref. 12). By assuming that 3 to 5 m^3 of air would be breathed during an 8-hour workday (less air is breathed during sleep at night), it can be estimated that a manganese intake in the range of 90 to 150 mg per day is required to induce manganism. This is provided the worker is exposed to this concentration for the entire 8-hour work period.

Typically, clinical effects do not become apparent until exposure has occurred for several years, but some individuals may begin to show signs after as little as 1-3 months of exposure. Currently available studies are not adequate to define the dose-response curve or the threshold for neurotoxicity (Ref. 6).

2.2.2 Production and Use

Manganese ore is principally mined in open-pit or shallow underground mines. Most manganese ore is used to produce ferromanganese (a manganese-iron alloy widely used in the production of steel) by smelting in the electric arc furnace. Approximately two tons of manganese ore are required to make one ton of ferromanganese. Production of 97%-98% pure manganese metal is achieved by aluminum reduction of low iron-content manganese ore, or from the byproducts of ferromanganese production. Manganese of higher purity is produced electrolytically from manganese sulfate solution (Ref. 6).

Metallic manganese (ferromanganese) is used principally in steel production to improve hardness, stiffness and strength. It is used in carbon steel, stainless steel, high-temperature steel, and tool-steel, along with cast iron and superalloys. Manganese compounds have a variety of uses. Manganese dioxide is commonly used in production of dry-cell batteries, matches, fireworks, porcelain and glass-bonding materials, amethyst glass, and as the starting material for production of other manganese compounds. Manganese chloride is used as a precursor for other manganese compounds, as a catalyst in the chlorination of organic compounds, in animal feed to supply the essential trace minerals, and in dry-cell batteries. Manganese sulfate is used in glazes and varnishes, in ceramics, fertilizers, as a fungicide, and as a nutritional supplement. Potassium permanganate is used as an oxidizing agent, a disinfectant, an anti-algal agent, for metal cleaning, tanning, bleaching, and as a preservative for fresh flowers and fruits (Ref. 6).

2.2.3 Essential in Steel Making

The chemical properties and metallurgical characteristics of manganese enable it to perform several essential functions when alloyed in iron. As compared with iron, manganese has a stronger affinity for oxygen, sulfur and carbon. When added to molten iron, manganese reacts with oxygen contained in the melt to form manganese oxide

(MnO). This reaction does not go to completion to take up all of the oxygen present, but proceeds to a point of balance or equilibrium. Therefore, although manganese is a deoxidizer, it is not as powerful in this respect as some other elements, like aluminum and silicon. The manganese in the melt also combines preferentially with any sulfur present to form manganese sulfide (MnS), a compound that has only limited solubility in the molten iron and rises to escape in the slag if conditions permit. Manganese sulfide is also insoluble in the solid metal, where it appears as non-metallic inclusions. This manganese sulfide is solid at the melting temperature of iron; hence its combination with sulfur prevents the formation of liquid iron sulfides at the temperatures required to hot work steel. Manganese is unique in this role, as there is no other element in the Periodic Table that can neutralize the harmful effect of sulfur on steel. Any manganese, beyond the amount required to combine with all of the sulfur present, will combine with the carbon in the steel to form manganese carbide (Mn_3C) as the steel cools through the Ar_1 critical point. The properties of manganese carbide and the appearance of particles of Mn_3C in the microstructure are indistinguishable from iron carbide. Manganese also promotes greater strength by increasing the hardenability of steel, and it usually tends to improve fracture toughness.

The most essential function of manganese in steel is the control of sulfur. Sulfur in steel forms iron sulfide (FeS), which has a relatively low melting point (approximately 1200°C or 2200°F) as compared with the solidus of iron. Furthermore, iron sulfide is insoluble in solid iron and steel, and it forms a eutectic composition with the iron that has a solidification point much lower than the compound. The eutectic of iron and iron sulfide solidifies at 998°C (1810°F); and because of its low liquidus and tendency to segregate, it is a potent cause of hot shortness or hot cracking. Quite early in dealing with the hot shortness problem caused by sulfur, steel makers found that adding sufficient manganese would eliminate the formation of low-melting iron sulfide. Manganese has a much stronger affinity for sulfur and forms manganese sulfide inclusions that have substantially higher melting temperatures. Manganese sulfide also dissolves any iron sulfide that happens to form. Therefore, the steel can be heated for hot working at temperatures normally used without incipient melting of the nonmetallic (sulfide) inclusions. A manganese content of four times the sulfur level is sufficient to suppress most of the hot shortness in steel that can be caused by sulfur, but the amounts of manganese regularly included typically exceed this remedial level because of additional alloying benefits provided by the manganese and to overcome the effects of segregation in the cast metal (Ref. 13).

2.3 Welding Fume

The chemical compounds originating during welding enter the human body primarily by inhalation of fine, airborne particles. Approximately 85-90% of these particles are from the filler metal of consumable electrodes and any covering or core materials they may contain. The composition of the filler is usually similar to that of the metal being welded. The heat generated during welding is sufficient to vaporize a significant amount of the electrode metal. The vapor travels out of the high-temperature welding arc and quickly condenses into sub-micron particles, which incompletely react with atmospheric oxygen and later agglomerate through electrostatic forces and moisture absorption. Agglomerates small enough to remain airborne are called welding fume.

Fume particles are of complex chemistry, spherical in shape, and typically found as chains or clusters of spheres. See Figure 2.1. While the chemical composition of the welding fume is similar to that of the electrode, certain elements, such as manganese and copper, are enriched beyond what is found in the consumable itself. The base metal weld pool is much cooler than the electrode tip, so the base metal is a significant contributor to total fume only when it contains a volatile protective coating or volatile alloying elements (Ref. 14).

This description of welding fume does not take into account the volatile coatings that are potentially on the work piece. These coatings, such as paint, primer, plastic, rust, oil, zinc or cadmium, produce fume that contributes to the total fume amount, but are not considered welding fume since the coating can be removed to avoid this additional fume.

2.4 Variables Affecting Fume Characteristics and Worker Exposure

2.4.1 Welding Process

As stated earlier, the welding process has a significant effect on the composition and amount of fume that is generated. Processes that incorporate flux with the electrode, such as SMAW or FCAW, produce more fume than bare wire processes like GMAW and GTAW. Figure 2.2 emphasizes the relative fume producing capabilities of various welding processes.

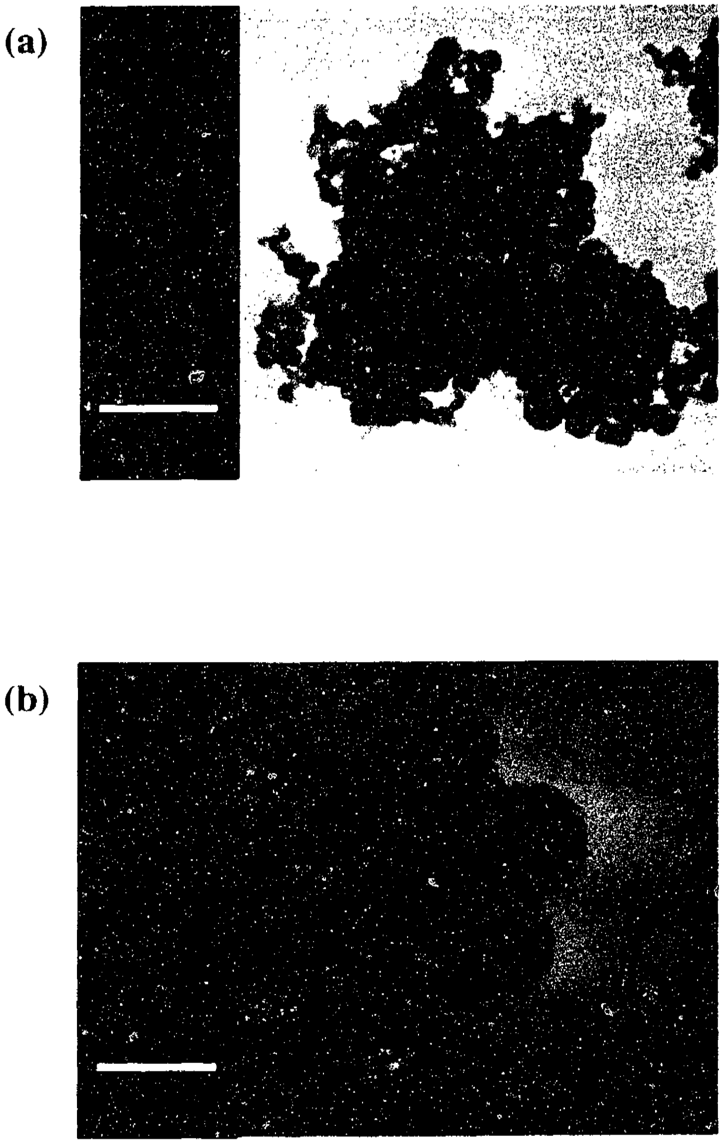

Figure 2.1: GMAW fume: (a) cluster of fine particles; (b) chain of fine particles.

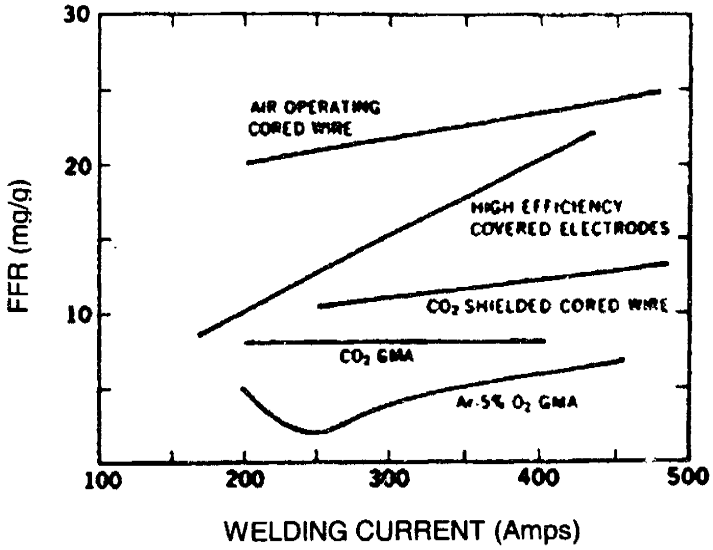

Figure 2.2: Comparison of fume formation rates for major arc welding processes (Ref. 15).

2.4.2 Welding Parameters

In addition to the welding process, the welding parameters affect fume generation. Both welding voltage and current affect fume generation. As the voltage increases, the arc length increases and allows a greater amount of time for the droplet to "boil" and emit fume. The welding current is proportional to the amount of material melted and influences the type of metal transfer that occurs. In general, as current level increases, fume levels will increase as well. The British Occupational Hygienic Society (Ref. 16) stated that, under standardized welding conditions, a given electrode will give consistent fume levels and composition, but that the levels could be greatly influenced as follows:

1. A 10% increase in amperage could cause a 35% increase in fumes.
2. Switching DC polarity from negative to positive would give a 5% increase.

3. Fillet welds give off 30% less fume than flat (down hand) welds.
4. Shallow (20°) electrode angles produce twice as much fume as a more normal 60° to 65° angle.
5. A long arc could result in a 50% fume increase.

2.4.3 Worker Habits and Workplace

Welding parameters, consumables and process all affect the level of welding fume generated, making it difficult to predict what the welder exposure will be. In addition, the welder himself has perhaps the greatest impact on actual exposure. The position of the welder's breathing zone (typically defined as being within about nine inches (23 cm) of the nose and mouth) with respect to the plume rising from the arc has the greatest influence on the level of individual fume exposure. The closer to the plume, the higher the exposure will be (Ref. 17). Anderson (Ref. 18) states that occasional sampling of welders in a group is not representative of individual or group exposure on a long term basis. By observing welders it was noted that some worked with their heads in the plume, some never put their heads in the plume, and the rest alternated back and forth. Each individual welder controlled the exposure to fume and gases by the method of performing the task.

Personal welding habits, the position of the work with respect to the welder, the duration of exposure, engineering controls, and the type of protective equipment worn will all affect worker exposure levels. Welding emissions can also vary from workplace to workplace, as well as among work areas within an individual workplace (Ref. 19). A welder working in an enclosed space is much more likely to be exposed to fumes at a higher level than one working in an open or well-ventilated area.

2.4.4 Valence State

Another variable to consider is the valence of the elements present in the fume. For example, hexavalent chromium in stainless steel welding fume is carcinogenic, while trivalent chromium is not. Voitkevich (Ref. 20) asserted that manganese toxicity in welding fume is enhanced as its oxidation state increases. Most manganese in welding fume is found as Mn^{+2}, as in MnO. However, he felt that some studies do not include the probability of manganese compounds with higher oxidation states existing under various welding conditions.

2.4.5 Particle Size

Particle size distribution is another important factor in determining the hazard potential of welding fumes, since it is an indication of the depth to which particles may penetrate into the respiratory system and the percentage of particles that will be retained therein. Welding fume particles can be classified in three categories (Ref. 21):

1. Particles greater than 5.0 µm in diameter, which are trapped before they reach the lungs on the walls of the human airway and are expelled in the mucus.
2. Particles ranging in diameter from 0.1 µm to 5.0 µm, which are respirable and penetrate and remain in the alveolar region.

3. Particles less than 0.1 µm, which act like a gas and are usually inhaled and exhaled without retention.

Toxicity in the lung is proportional to residence time. Fume particles of the critical size (0.1 µm to 5.0 µm diameter), are difficult for the lung macrophages to remove, have a longer lung residence time, and are therefore the most toxic (Ref. 21).

Fasiska (Ref. 22) found that most welding fumes consist of particles 0.1 µm to 1.0 µm in diameter and pointed out that a simple weight percent analysis of the various particle sizes does not provide adequate information since the size of the particle and its chemistry affects toxicity. For example, a few large particles may dominate the weight percent analysis, but if the particle diameters were greater than 5.0 µm, they would not be expected to reach the lower respiratory system, whereas material present as fine particles could penetrate to the alveoli and be absorbed into the blood.

It has also been recognized in the literature that, at certain temperatures and humidity, agglomeration can lead to particle growth and render harmless a potentially dangerous fume. Rudell *et al* (Ref. 23) found that particle growth by agglomeration was a function of temperature, humidity and deposition. They maintained that a respirable particle could increase its size by agglomeration when it entered the respiratory tract and, therefore, could deposit earlier in the airway than would normally be expected. Thus, the particle would not reach the alveoli, where it could be subsequently absorbed into the body system.

CHAPTER 3

REGULATORY FRAMEWORK

3.1 Introduction

The growth of occupational hygiene and worldwide legislative developments over the past thirty years has resulted in increasing recognition of the effect of working conditions upon the health of the workforce in many industries, including the welding industry. This awareness has been created by cumulative experience with a variety of airborne pollutants that have been shown to be responsible for adverse physical effects long before hazards arising from working conditions were suspected. Thus, a climate of opinion has evolved regarding the importance of occupational hygiene, which, together with an increase in the specific knowledge of the nature and effect of atmospheric pollutants, has resulted in the formation of regulation and controls of increasing stringency (Ref. 24).

This section will describe the agencies that regulate workplace hazards, along with their evaluation criteria. The importance of these regulations to the welding industry will then be discussed with regard to total welding fume and manganese.

3.2 Agencies and Exposure Limits

Control of industrial health and safety in the United States is provided under federal legislation, which is supported by technical agencies whose duties are variously administrative and investigative. The structure of control is important because it generates regulations for airborne pollutants, such as welding fume, which are adopted by most other industrialized nations. This structure is summarized in the following sections.

3.2.1 OSHA

In 1970, the Occupational Safety and Health Act (OSHAct) was enacted by Congress to control the health and safety of employees in the U.S. The Occupational Safety and Health Administration (OSHA) was established in the Department of Labor (DOL) to administer the OSHAct. As defined in its enabling legislation, OSHA's mission is to "Assure so far as possible every working man and woman in the Nation safe and healthful working conditions (Ref. 25)." This mandate involves the application of a set of tools by OSHA (e.g., standards development, enforcement, compliance assistance) which enable employers to maintain safe and healthful workplaces.

OSHA sets Permissible Exposure Limits (PELs) to protect workers against the health effects of exposure to hazardous substances. PELs are regulatory limits on the amount or concentration of a substance in the air. They may also contain a skin designation. PELs are enforceable. OSHA PELs are based on an 8-hour time weighted average (TWA) exposure. When setting PELs, OSHA is required to consider the feasibility of controlling exposures in various industries where the agents are used.

Many PELs were set based on data obtained in the 1950s and 1960s. New information developed since that time has made some of those limits obsolete. In response, OSHA has developed a program to systematically and continuously update PELs (Ref. 26).

3.2.2 NIOSH

Also created under the OSHAct, the National Institute for Occupational Safety and Health (NIOSH) is located in the Centers for Disease Control and Prevention (CDC), under the Department of Health and Human Services (DHHS). The OSHAct legislation mandated NIOSH to conduct research and education programs separate from the standard and enforcement functions conducted by OSHA.

NIOSH is responsible for conducting research on the full scope of occupational disease and injury ranging from lung disease in miners to carpal tunnel syndrome in computer users. In addition to conducting research, NIOSH:

- investigates potentially hazardous working conditions when requested by employers or employees;
- makes recommendations and disseminates information on preventing workplace disease, injury, and disability; and
- provides training to occupational safety and health professionals (Ref. 27).

NIOSH field staff employ environmental evaluation criteria in determining Recommended Exposure Limits (RELs). These criteria are intended to suggest levels of exposure to which most workers may be exposed up to 10 hours per day, 40 hours per week for a working lifetime without experiencing adverse health effects, and are based primarily on concerns relating to the prevention of occupational disease (Boilermaker's).

3.2.3 ACGIH

The American Conference of Governmental Industrial Hygienists (ACGIH) is a private, member-based organization and community of professionals that advances worker health and safety through education and the development and dissemination of scientific and technical knowledge.

Undoubtedly the best known of ACGIH's activities, the Threshold Limit Values for Chemical Substances Committee was established in 1941. This group was charged with investigating, recommending, and annually reviewing exposure limits for chemical substances. It became a standing committee in 1944. Two years later, the organization adopted its first list of 148 exposure limits, then referred to as Maximum Allowable Concentrations. The term "Threshold Limit Value (TLV®)" was introduced in 1956. The first Documentation of the Threshold Limit Values was published in 1962. Today's list of TLV®s includes more than 700 chemical substances and physical agents (Ref. 28). It is usual to define TLV®s in terms of their concentrations in air, either in milligrams per cubic meter (mg/m^3) for particulates or parts per million (ppm) for gases. ACGIH states that TLV®s are guidelines.

Three categories of TLV®s are now specified for airborne pollutants in workplace atmospheres as follows (Ref. 24):

3.2.1.1 TLV® - Time Weighted Average (TLV® - TWA)

This is the average concentration for an 8-hour workday or a 40-hour workweek to which nearly all workers may be repeatedly exposed, day after day, without adverse health effects (where the term TLV® is used alone in this text, it will refer to the TLV® - TWA).

3.2.1.2 TLV® - Short Term Exposure Limit (TLV® - STEL)

This is the maximum concentration to which workers can be exposed for a period of up to 15 minutes continuously without suffering (i) irritation, (ii) chronic or irreversible tissue damage, or (iii) narcosis of sufficient degree to increase accident proneness, impair self-rescue, or materially reduce work efficiency provided that no more than four excursions per day are permitted, with at least 60 minutes between exposure periods, and provided that the daily TLV® - TWA is not exceeded. The STEL should be considered a maximum allowable concentration or absolute ceiling, not to be exceeded at any time during the 15-minute excursion period.

3.2.1.3 TLV® - Ceiling (TLV® - C)

This is the concentration that should not be exceeded even instantaneously. All listed substances are assigned a TLV® - TWA and a TLV® - STEL, but only a few, notably those that have a rapid effect on the human body, are assigned a TLV® - C.

3.3 Regulations on Airborne Pollutants

In order to be effective, atmospheric pollution legislation defines permissible exposure levels of airborne pollutants. There are numerous materials that can contaminate industrial atmospheres and the nuisance, irritant, toxic and carcinogenic properties of these materials differ widely. Similarly, the degree of hazard depends not only upon the atmospheric concentration of a given pollutant, but also on the frequency and duration of exposure and, in some cases, the physical state of the pollutant. Ideally, the legislation would define maximum safe atmospheric concentrations of all possible air pollutants under a variety of exposure conditions. Two sets of regulations are generally defined; those applying to the working area and those applying to substances emitted more widely into the general environment. Compliance with this definition must be based upon measurements of real breathing zone concentrations rather the laboratory experiments. Thus, in the context of welding, it is the regulation applying to the working area which assumes the greater importance, and it is the breathing zone concentrations of fume which must be controlled (Ref. 24).

3.4 Regulations on Total Welding Fume

In 1989, the OSHA PEL for total welding fume was set at 5 mg/m^3 as an 8-hour TWA; however this limit was vacated and is currently not enforceable. Since 1989, OSHA has not reestablished a PEL for total welding fume; however, individual PELs have been set for the various constituents that are found in welding fume. The PEL for manganese will be discussed in the following section. OSHA has also set a PEL for total particulates not otherwise regulated (PNOR) at 15 mg/m^3 as an 8-hour TWA (Ref. 29).

NIOSH indicates that it is not possible to establish an exposure limit for total welding emissions since the composition of welding fumes and gases vary greatly, and the welding constituents may interact to produce adverse health effects. Therefore, NIOSH suggests that the exposure limit for each welding fume constituent should be met, and they have established a REL for welding fumes (and total particulates) of the lowest feasible concentration. NIOSH considers welding fumes as potential occupational carcinogens (Ref. 30).

The ACGIH has assigned welding fumes-total particulate not otherwise classified (NOC) a TLV® - TWA of 5 mg/m^3 for a normal 8-hour workday and a 40-hour workweek. The ACGIH also recommends that conclusions based on total fume concentration are generally adequate if no toxic elements are present in the welding rod, metal, or metal coating and if conditions are not conducive to the formation of toxic gases (Ref. 31).

3.5 Regulations on Manganese

The current acceptable exposure limits for manganese fume (as manganese) have been set by the agencies described above. The OSHA PEL for manganese is 5 mg/m^3 as a ceiling value for general industry and 5 mg/m^3 as a TWA for the construction industry.

NIOSH has set two RELs for manganese fumes; one as a 1 mg/m^3 TWA, and one as a 3 mg/m^3 STEL.

In 1995, ACGIH reduced the TLV® - TWA for manganese fume (as elemental and organic compounds) from 1 mg/m^3 to 0.2 mg/m^3 (Ref. 32). It is this TLV® that is expected to be of the most concern to the welding industry.

The various U.S. exposure limits for total welding fume and manganese fume are summarized in Table 3.1. The manganese exposure limits can be compared with some international worker exposure standards in Table 3.2.

Table 3.1. Allowable exposure limits for U.S. agencies. All values are given in mg/m^3.

	OSHA	**NIOSH**		**ACGIH**
	PEL - C	**REL - TWA**	**REL - STEL**	**TLV® - TWA**
Welding Fume	--	Lowest feasible concentration		5
Manganese	5	1	3	0.2

Table 3.2. Allowable exposure limits for some industrial countries. All values are given in mg/m^3 (Ref. 33).

France **VME**	**Germany** **MAK**	**Norway**	**Russia** **MAC**	**Sweden** **NGV**	**New Zealand PEL**	**U.K.** **OEL**
1	1	1	0.2	1	1	0.2

3.5.1 Which Regulations Apply?

It should be noted that industry is legally required to meet only those levels specified by OHSA PELs. While OSHA has no immediate plans for reducing the exposure limit for manganese, many organizations control worker exposure to the lowest published accepted standard, and will likely use ACGIH TLV®s. For much of industry, TLV®s are used to govern exposures to those materials that are listed and found in the welding environment.

3.5.2 Other Industries

The regulations for manganese, which are to be applied to welding fumes, are not based on any studies involving welding fumes, but were developed entirely in unrelated industries. To illustrate, the manganese exposure limits that would apply to welding fumes were developed based on experiences in manganese mines and foundries, battery (dry cell) plants, and electroplating plants. In each of these industries, workers are potentially exposed to manganese fumes in higher and purer concentrations than those found in welding fume. Due to the complex nature of the welding environment, there is some concern among the welding community whether the same exposure limits that were developed in these industries should apply to manganese found in welding fume. The following chapters will discuss manganese particular to the welding environment and examine the feasibility of these regulations for the welding industry.

CHAPTER 4

MANGANESE, HEALTH, AND WELDING

4.1 Do Current Exposure Limits Make Sense?

The overall issue under consideration in this thesis is whether or not the current exposure limits for manganese, particularly the ACGIH TLV® - TWA of 0.2 mg/m^3, should be applicable to the welding industry. The current exposure limits were not developed based on data developed from welding fume. Because of the complex nature of welding fume, some question has arisen over whether the single TLV® for manganese makes sense for use with welding fume, which contains other elements, particularly iron, along with the manganese, in a variety of chemical forms. This question is important because of social, economic, safety, and litigation issues.

Is there evidence of manganese harm to welders? Although manganism among manganese miners and foundry workers is well documented, there is no evidence in the literature to suggest any correlation between welders and chronic manganese poisoning. In fact, a 1981 study by Chandra *et al* (Ref. 34) has been the only investigation to suggest a correlation. This study, however suggested only a "possible occurrence of manganese poisoning among welders" as a hypothesis in the introduction, and stated in its conclusions that "Further studies on a large number of welders may help us in drawing definite conclusions." However, this "possible" suggestion was not supported by concrete evidence.

An epidemiological study that investigated the effects on the nervous system among welders exposed to manganese reported that "The neurotoxic effects found in groups of welders exposed to manganese are probably caused by the manganese exposure." This study also found that "these welders did not have higher concentrations of manganese in blood than the controls." (Ref. 35) This evidence of a possible link between welding fume exposure and manganism is also only speculative and is far from a scientific conclusion.

Other studies (Refs. 36, 37, 38, 39) have found that welders did not exhibit any signs of manganese intoxication. An epidemiological study performed on workers at Caterpillar concluded that welders did not experience a greater incidence of disease or health problems than non-welders (Ref. 40). As shown, the evidence pertaining to this issue is sparse, speculative and has generated a fair amount of controversy. The following sections will present additional information that should help to clarify the issue.

4.2 Manganese in Welding Fume

4.2.1 Oxidation State

Manganese is not found as a pure element in welding fume, rather it is present in compounds with other elements. These compounds are typically oxides, but can also include fluorides, compounds with iron, silicon, potassium, and a variety of other elements. Manganese toxicity depends on its oxidation state and the type of compounds containing this element. The toxicity rises as the oxidation state of the manganese increases. Voitkevich (Ref. 20) used X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD) to study welding fume and concluded that Mn^{2+}, as opposed to Mn^{4+}, was the most probable oxidation state of manganese in welding fume. Mn^{4+}, as in MnO_2, is considered more toxic than Mn^{2+}, as in MnO, but the latter is the most probable state in welding fume. Minni *et al* (Ref. 41) used electron spectroscopy to determine oxidation states of the main metal constituents in the fume derived from mild steel welding with covered electrodes. Manganese was found to occur with valences of +2 and +3. Thus, the toxicity of manganese in welding fume is lower than that of the pure oxide, MnO_2. It is the pure oxide that would typically be encountered in manganese mines and foundries.

4.2.2 Amounts

A variety of investigators have reported manganese levels in welding fume (Refs. 42, 43, 44, 45). The values from these reports vary between 1% and 15% of the total welding fume on a weight basis. However, some of these investigators are reporting percent of cations in the total fume, so the total manganese content by weight would be lower. It is believed that, typically, the manganese fume concentration for mild or low-alloy steels is in the range of 3 to 5 percent by weight manganese cation as a fraction of the total weight (Ref. 46).

4.2.3 Sometimes Exceeds Current ACGIH TLV® - TWA

Although in the majority of situations welders are exposed to less than the current ACGIH TLV® - TWA of 0.2 mg/m^3, there are conditions where this limit value is exceeded. As Castner (Ref. 47) states, "Only a few of the tests showed levels of Mn above the exposure limit. However, work at high production rates or in enclosed and confined spaces has the potential for exposure that could exceed the anticipated levels."

A study by Korczynski (Ref. 48) found that 26 of 42 welders studied were over-exposed to manganese when compared with the current guideline, and revealed that the welders' personal exposures to manganese ranged from 0.01 to 4.93 mg/m^3 as a TWA. In a study conducted by NIOSH (Ref. 29) on stainless steel welds made with SMAW electrodes, 28% of the tests made with various welder positions and ventilation conditions showed manganese levels above the TLV®. Lyttle (Ref. 17) suggests that in order to maintain manganese exposure to welders below the TLV®, the total fume level would need to be limited below 2 to 3 mg/m^3. He goes on to state that the implications of controlling fume to this level are significant, but that it can be accomplished by careful selection of consumables and welding processes and proper use of ventilation. It should be remembered that the current acceptable standard for total welding fume is a TLV® - TWA of 5 mg/m^3.

4.3 Welder Intake of Manganese

As noted in section 2.2.1, chronic manganese poisoning has not been reported below intake amounts on the order of 90 to 150 mg per day. In this section, a series of calculations are performed in order to determine if welders are at risk of manganese intake in this range.

Initially, it will be assumed that the ACGIH TLV® - TWA of 5 mg/m^3 for total welding fume is being met. It has been determined that a human breathes about 10 m^3 of air in a 24-hour period (Ref. 12). Because less is breathed during sleep at night, it will be assumed here that a worker breathes 5 m^3 in an 8-hour workday. Using these values, the amount of total welding fume breathed in a day can be calculated:

$$(5\ mg/m^3)(5\ m^3/8\text{-}hr\ day) = 25\ mg\ of\ total\ welding\ fume\ per\ 8\text{-}hr\ day.$$

As discussed in section 4.2.2, manganese content in welding fume varies between 1 and 15 percent by weight. Here an average value of 8 wt. % will be assumed. Using this value with the calculated value for total fume, the amount of manganese potentially ingested by a welder can be calculated:

$$(0.08)(25\ mg\ of\ total\ welding\ fume\ per\ 8\text{-}hr\ day) = 2\ mg\ of\ manganese\ per\ 8\text{-}hr\ day.$$

Thus, it is evident that under average conditions it is impossible for a welder to inhale enough manganese from welding fume to approach the amounts required to induce manganism. Even if the TLV® for fume concentration is exceeded to 20 mg/m^3 and a higher manganese percentage in the fume of 15 wt. % is assumed, this still appears to be the case:

$$(20\ mg/m^3)(5\ m^3/8\text{-}hr\ day) = 100\ mg\ of\ total\ welding\ fume\ per\ 8\text{-}hr\ day;$$

$$(0.15)(100\ mg\ of\ total\ welding\ fume\ per\ 8\text{-}hr\ day) = 15\ mg\ of\ manganese\ per\ 8\text{-}hr\ day.$$

Here, 15 mg of manganese per 8-hr day is still well below the 90 to 150 mg per day required for manganism.

To emphasize the point that welders are not exposed to enough manganese to cause manganese poisoning, further calculations can be made. Directly in the welding plume, the fume concentration is about 100 mg/m^3. This value can be substituted into the previous calculations:

$$(100\ mg/m^3)(5\ m^3/8\text{-}hr\ day) = 500\ mg\ of\ total\ welding\ fume\ per\ 8\text{-}hr\ day;$$

$$(0.15)(500\ mg\ of\ total\ welding\ fume\ per\ 8\text{-}hr\ day) = 75\ mg\ of\ manganese\ per\ 8\text{-}hr\ day.$$

Thus, if a welder worked with his face directly in the welding plume and was able to breath the full concentration for 8 hours, assuming the high estimate of 15 wt. % manganese in the fume, he would potentially be able to inhale 75 mg of manganese, which is still below the amount observed for manganism. This is, however, a nonsensical situation. First, the welder's helmet would prevent breathing of the full concentration. Also, it is believed that a human could not tolerate 100 mg/m^3 for more than a few minutes without coughing or gagging. One's eyes, nose and throat would become severely irritated well before the manganese dose becomes excessive. The plume of a bonfire is on the same order of concentration; one can imagine what it would be like to stand downwind of a bonfire for 8 hours. It is also believed that someone would have a difficult time working for more than an hour in a concentration of 20 to 30 mg/m^3 of total fume without significant discomfort (Ref. 49). A welder would, therefore, remove himself from the situation if the fume concentration became excessive for more than a short period of time.

From these calculations, it appears that typical welders are not exposed to manganese in amounts significant to cause manganism. This is consistent with the lack of evidence of this effect in the literature.

4.4 Biological Transport of Manganese

Even assuming the calculations in the previous section are incorrect, there is a mechanism that suggests manganese contained in welding fume carries its own antidote because of its presence with iron, which comprises a large fraction of steel welding fume.

An important determinant in the neurotoxicologic outcome of metal exposure is the rate and means of transport from the blood plasma into the brain across the capillary endothelial cells that comprise the blood-brain barrier (BBB). To cross this barrier, metal ions or their complexes must be either highly lipid soluble, or possess affinity for specific carrier-mediated transport systems within the endothelial plasma membrane (Ref. 50).

Iron is transported across the BBB by the transporter protein, transferrin. There is also evidence that manganese is also transported across the BBB by transferrin, and is modulated by plasma iron homeostasis (Ref. 51). It has been hypothesized that manganese transport across the BBB has a negative correlation with iron concentration. There are at least two reasons why this is plausible. First, iron and manganese compete for the same transporter protein, transferrin. Thus, the more iron is competing for the same carrier, the less the carrier will be available to transport manganese. Second, there is evidence the amount of transferrin receptor is regulated by the availability of iron. As the amount of iron goes up, the amount of receptor goes down. Thus, it is expected that as iron in the lungs is increased, the amount of transporter molecules will be downregulated, which should further diminish manganese transport across the BBB (Ref. 52).

It has also been shown that manganese transport rates across the air-blood barrier in the lungs and capillaries are influenced by the history of iron exposure, much in the same way as described for the BBB (Ref. 52).

It has been shown that iron exposure significantly exceeds manganese exposure in welding fume from mild steel and stainless steel (Ref. 48). Because welders never inhale manganese without inhaling significant amounts of iron at the same time, the evidence described above suggests that by the very nature of their jobs, welders may be at a reduced risk for manganese induced illness.

4.5 Other Issues

There are other issues that need to be considered when regulations for manganese exposure from welding fume are being developed. Some of these issues are discussed in the following sections.

4.5.1 Differences Between Manganism and Parkinson's Disease

In a recent court case involving alleged welding-induced manganism (Ref. 53), it was pointed out that workers who suffer from idiopathic Parkinson's disease might have mistakenly been diagnosed with manganism. The medical doctors serving as expert witnesses in this case discussed the differences between the two diseases and suggested some reasons for this mistake.

Parkinsonism is a group of symptoms that are similar to the symptoms seen in Parkinson's disease. These symptoms may be grouped into four sets. The first set is tremors; in Parkinson's disease the tremors occur while the person is at rest. The second set of symptoms is rigidity, which is a stiffness and resistance to movement in the limbs. The third set of symptoms is called bradykinesia, which means slow movement. This set of symptoms includes difficulty in initiating and carrying out a wide variety of movements. The fourth set of symptoms is imbalance or loss of postural reflexes.

Both manganism and Parkinson's disease are types of parkinsonism. Idiopathic Parkinson's disease is Parkinson's disease without a known cause. When manganese is the cause of a patient's parkinsonism, the condition is referred to as manganism or manganese-induced parkinsonism. Because different parts of the brain are involved in the two diseases, a patient's response to medication can be used to distinguish the diseases. The part of the brain involved in Parkinson's disease is the substantia nigra pars compacta. The part of the brain involved with manganism is primarily the globus pallidus. These two parts of the brain are both located in the basal ganglia region. Patients with damage to the substantia nigra lose the ability to connect to cells downstream, which is normally achieved with a chemical called dopamine. Because the rest of the system is intact, these patients respond when treated with levodopa, a dopamine replacement. Patients with damage downstream, in areas such as the globus pallidus, will not respond in a meaningful way to dopamine replacement because the system is incapable of responding to dopamine.

The death of neurons in the substantia nigra and the resulting reduction in dopamine production causes the symptoms of idiopathic Parkinson's disease. Patients with this condition have a resting tremor that tends to begin on one side rather than symmetrically. In addition these patients have a good response to levodopa. This is in contrast to patients who have manganism, who do not exhibit tremor, but have speech disturbances, gait disturbances, and poor if any, response to levodopa.

One of the expert witnesses testified that approximately one million people in North America have idiopathic Parkinson's disease, while manganese intoxication as a result of exposure in the workplace is "extremely rare," and he had never seen a case in the United States. He also explained that some older reports suggested that the dopamine system was involved in patients with manganism, but the authors did not know how to tell the difference between Parkinson's disease and manganism. He further explained that literature from the 1960s and 1970s probably confused the two diseases. He pointed out that there was an article by Dr. Cotzias (Ref. 54) that included references to patients with manganism who had responded to levodopa. However, autopsies had revealed that some of these patients had pathology in the substantia nigra, which is not the location of manganese pathology (Ref. 55).

4.5.2 Combined Element Effects

Welding fume is made up of a complex mixture of elements and compounds, which may lead to difficulties in applying single exposure limits for the individual elements contained in the fume. Welding fume consists of six to ten elements depending on the type of welding. By comparison, it can be imagined that a doctor prescribes six to ten medicines to a patient at the same time. It is likely that there is low confidence that the effect of every medicine does not change when they are taken jointly. Although the analogy is rough, the same may be assumed for the toxic action of the elements found in welding fume. The biological effect of a leading toxic element may be changed in one or another direction in the presence of other elements. Besides, one element may simultaneously enter into several compounds, the biological effects of which are different (Ref. 20). As another author puts it: (Ref. 56)

> The discussion of exposure to toxic materials thus far has focused on the establishment of a safe level for an isolated substance. This make-believe world of isolated hazards does not exist in either the workplace or in the general environment. Most potential human exposure to chemicals is exposure to mixtures. Toxic materials exist in combinations with one another, and their effects may be further complicated by stress caused by noise, abnormal temperatures, ergonomic factors, and psychosocial factors. Two toxic substances in combination can have effects on the body which are either (1) *additive* in an expected way, (2) *synergistic* (i.e., combining in such a way that the resultant effect is greater than the sum of the individual effects), or (3) *antagonistic* (i.e., combining in such a way that the resultant effect is less than the sum of the individual effects).

The discussion in section 4.4 suggests that iron and manganese in combination have an antagonistic effect on the body. Voitkevich (Ref. 20) suggested a synergistic effect when manganese is combined with silicon and fluorine in welding fume, and discourages the use of elemental TLV®s, which were determined from simple compounds, for chemicals of complex elemental composition.

4.5.3 Problems

There are some problems that must be considered and for which solutions must be discovered if sensible and feasible exposure limits for welding fume and the elements contained within are to be established.

4.5.3.1 Measuring Exposure

The methods of sampling fume and gases generated by a given welding process are fundamental to the success of any survey of welding workshop atmospheres. Many of the published figures for welding fume measurements in the past have shown order of magnitude variations. While these results reflect only the variable fume potential of a process in terms of welding conditions, consumable size, and operator variables, inconsistencies may also be a function of unsatisfactory sampling procedures, or inadequate logging of procedural features such as sample position and ambient ventilation conditions (Ref. 24).

Because of the great variance in the habits of welders, as discussed in section 2.4.3, obtaining representative exposure samples becomes very difficult. There are other environmental variables, including ventilation, that contribute to the difficulties in obtaining representative samples of welding fume in the welder's breathing zone. Due to this difficulty in measuring exposure, there has been much controversy over the effects of manganese and other elements in welders' exposure. This is an issue that must be resolved if an enforceable exposure standard is to be established.

4.5.3.2 Total Fume vs. Welding Fume

The problem of collecting representative fume samples can be further compounded because of coatings on the work piece, which are vaporized by the heat of the welding arc. For example, when a welding fume sample is taken from a job site where oil may be on the work piece, the fume may contain the typical metal oxides from the materials being welded, along with decomposition products or vapor from the evaporation of the oil. Volatile coatings that may be found on the work piece may include paint, primer, plastic, rust, oil, zinc, cadmium, or degreasing solvent. Some of these coatings may have been placed on the work piece intentionally, while some are nuisance contaminants. In any case, they serve to dilute the amount of manganese as a percent of the total fume.

4.5.3.3 CO

Welding also produces carbon monoxide, which is toxic to humans, and can have neurological effects. Carbon dioxide and carbon monoxide are formed by the decomposition of organic compounds in electrode coatings and cores, from inorganic carbonates in coatings, and from carbon in the weld metal. Carbon monoxide is generated by the decomposition of carbon dioxide used in shielded arc welding processes (Ref. 14). It has been suggested that the poisoning effects of carbon monoxide have at times been mistaken for and attributed to manganese intoxication in welders (Ref. 49).

4.5.4 High-Manganese Materials

It should be noted that welders who work with high-manganese steels or surfacing materials may be more highly exposed to manganese. It has been shown that fume from high-manganese hardfacing electrodes contains 26 to 31 percent manganese by weight (Ref. 45). Caution should be taken in these situations to ensure that adequate ventilation and/or other engineering controls are put into place to reduce manganese exposure to the workers. Only a minute fraction of the total materials that are welded would fall into this category, however.

CHAPTER 5

FEASIBILITY

5.1 OSHAct and Feasibility

The Occupational Safety and Health Act of 1970 provided the statutory mandate for OSHA to promulgate workplace exposure standards. The relevant section of the Act reads:

> The Secretary, in promulgating standards dealing with toxic materials or harmful physical agents under this subsection, shall set the standard which most adequately assures, *to the extent feasible*, on the basis of the best available evidence, that no employee will suffer material impairment of health or functional capacity even if such employee has regular exposure to the hazard dealt with by such standard for the period of his working life. Development of standards under this subsection shall be based upon research, demonstrations, experiments, and such other information as may be appropriate. In addition to the attainment of the highest degree of health and safety protection for the employee, other considerations shall be the latest available scientific data in the field, *the feasibility of the standards*, and experience gained under this and other health and safety laws (emphasis added) (Ref. 57).

As emphasized by the italicized print in the previous section, standards promulgated by OSHA were intended by Congress to be "feasible." This term lends itself to some ambiguity and interpretation. Not surprisingly, the courts have been left with the task of interpreting what Congress intended the definition of "feasible" to be. Several court cases (Refs. 58, 59, 60, 61, 62) have weighed this question and have provided holdings on the issue, which form the judicial history and set the precedent by which further actions are judged.

The judicial history has established that there are two types of feasibility – technological and economic (Ref. 60). Two questions can then be asked, "Is it technically possible for an industry to meet the standard," and "What are the costs involved with meeting the standard, and are they merited by the benefits of meeting the standard." It has been left to the courts to decide to what degree the answers to these questions may be considered when setting standards. Economic feasibility is considered more pressing in regard to this thesis topic, and will be dealt with more fully here.

The general judicial criteria for economic feasibility can be summarized by referring to the following holdings:

- OSHA need not weigh industry costs against worker benefits (Ref. 62).
- A standard is not infeasible simply because it is financially burdensome (Ref. 58).
- Congress understood that the OSHAct would create substantial costs for employers, yet intended to impose such costs when necessary to create a safe and healthful working environment (Ref. 62).

Subsequent proceedings have solidified the interpretation that economic considerations are not to be considered when establishing worker exposure limits under the OSHAct, rather the standard ensuring worker health should be set, and the most feasible methods of compliance should be adopted (Ref. 63).

5.2 Costs and Compliance

In regard to manganese fume standards in the welding industry, technological feasibility is not considered problematic. Through various prevention methods and engineering controls, it is possible to meet the standards. However, there would be significant costs to the welding industry in meeting a standard of 0.2 mg/m^3 as a TWA for manganese fume. Because of the interpretation by the courts regarding economic analysis of the OSHAct feasibility standard, a detailed cost-benefit analysis is not presented here. Rather, the significant costs are noted and emphasized by discussing the actions that would be required by industry in meeting the standard.

5.2.1 Compliance

The various actions and methods that are available to the welding industry for lowering fume exposure to workers are discussed in this section. All of these generate substantial costs to industry.

5.2.1.1 Administrative Controls

Administrative controls are implemented to monitor the welding environment and to ensure that worker exposure does not exceed the established exposure limit. These controls include costs from medical surveillance, workplace monitoring and measurement, and written compliance programs.

A medical surveillance program should include education of employers and workers about work-related hazards, early detection of adverse health effects, and referral of workers for diagnosis and treatment. To detect and control work-related health effects, medical evaluations should be performed (1) before job placement, (2) periodically during the term of employment, and (3) at the time of job transfer or termination. In addition, biological monitoring, which involves sampling and analyzing body tissues or fluids to provide an index of exposure to a toxic substance, should be implemented (Ref. 64).

Workplace monitoring and measurement is accomplished through the use of special filters and analysis methods. Determination of a worker's exposure to airborne manganese fumes is made using a mixed cellulose ester filter (MCEF), 0.8 microns. Samples are collected at a maximum flow rate of 2.0 liters/minute until a maximum collection of 960 liters is reached. Analysis is conducted with either atomic absorption spectroscopy (AAS) or inductively coupled argon plasma (ICP/DCP-AES) (Ref. 32). All of the administrative controls require thorough record keeping.

5.2.1.2 Engineering Controls

Engineering controls allow the control of the welding environment within stated limits by the use of specific emission control equipment. Methods that are effective in controlling worker exposures to welding fumes, depending on the feasibility of implementation, are as follows:

- Process enclosure
- Local exhaust ventilation
- General dilution ventilation
- Personal protective equipment (Ref. 64)

Costs that are involved with these controls include equipment research and development, procurement, installation and maintenance, and personnel training in the use and maintenance of engineering controls (Ref. 65).

5.2.1.3 Personal Controls

Personal controls include the use of devices such as respirators, clean air welding helmets and protective clothing to shield workers from harmful amounts of fume.

According to OSHA, good industrial hygiene practice requires that engineering controls be used where feasible to reduce workplace concentrations of hazardous materials to the prescribed exposure limit. However, some situations may require the use of respirators to control exposure. Respirators must be worn if the ambient concentration of manganese fumes exceeds prescribed exposure limits. Respirators may be used (1) before engineering controls have been installed, (2) during work operations such as maintenance or repair activities that involve unknown exposures, (3) during operations that require entry into tanks or closed vessels, and (4) during emergencies. Workers should only use respirators that have been approved by NIOSH and the Mine Safety and Health Administration (MSHA).

Employers may be required to institute a complete respiratory protection program. Such a program must include respirator selection, an evaluation of the worker's ability to perform the work while wearing a respirator, the regular training of personnel, respirator fit testing, periodic workplace monitoring, and regular respirator maintenance, inspection, and cleaning. The implementation of an adequate respiratory protection program (including selection of the correct respirator) requires that a knowledgeable person be in charge of the program and that the program be evaluated regularly (Ref. 64).

5.2.1.4 Processes and Parameters

In some circumstances, worker exposure to welding fumes can be controlled through selection of alternate processes, parameters or materials. It has been shown that using pulsed current during gas metal arc welding (GMAW) can reduce the fume generation rate compared to steady welding current (Refs. 66, 67). The rapid "current rise" times and high frequency of pulsing allows for quick detachment of the metal droplets formed at the tip of the wire electrode. This minimizes the time spent "fuming" at the wire tip and thus decreases overall fume levels.

For a certain weld metal deposition rate, it is possible to use a variety of welding processes, and different amounts of welding fume can be generated for this same amount of deposited weld metal, depending on the welding process and consumables selected. Typically, solid wire used with argon-based shielding gases in fine droplet spray transfer mode provides one of the lowest levels of fume per amount of weld metal deposited. New "low-fume' flux-cored and metal-cored consumables have also been developed.

Much of this technology may be beneficial in that it reduces fume generation, however there are likely to be increased process or materials costs.

5.2.2 Productivity

There is a cost impact on productivity due to loss of worker time due to increased set-up time, reduced efficiency, schedule delays, and the medical surveillance involved with maintaining exposure limits (Ref. 65). Workers may also be limited in the time allowed to work on a job, so that fume exposure remains below the TWA for the prescribed exposure limit.

5.2.3 Discussion

As has been discussed in the previous section, it would be technically feasible to reduce welder exposure to below the ACGIH TLV® - TWA of 0.2 mg/m^3 for manganese fume. However, significant costs would be involved with meeting this standard, although these costs are lawfully not to be considered when setting the level of exposure that is most healthful to workers.

The evidence presented in this thesis demonstrates that manganese contained in welding fume affects the body in different ways than manganese from other industries, such as manganese mines and foundries, in which the manganese is present in a purer form. Because of this, the welding industry should not be under the same restrictions as the industries where this regulation was developed.

Thus, the costs of compliance with this standard are not justified, therefore they would be unnecessary and should be avoided. A reasonable standard, developed using data from welding fume studies, should be promulgated. This standard would then keep compliance costs at a level consistent with the degree of worker protection required for welders.

Litigation costs involved with the possible exposure limit of 0.2 mg/m^3 are also significant, and should be avoided, based on the evidence presented here.

CHAPTER 6

CONCLUSIONS

1. Welders are not typically exposed to manganese in excess of the OSHA PEL of 5 mg/m^3, however the ACGIH TLV® - TWA of 0.2 mg/m^3 is sometimes exceeded. Industry is legally required to meet only those levels specified by OHSA PELs, however, many organizations control worker exposure to the lowest published accepted standard, and will likely use the ACGIH TLV®.

2. The current manganese exposure limits were not developed using data from manganese in welding fume, but rather from other industries where the manganese may have been in a different concentration or chemical state. Thus, the manganese present in welding fume may not be equivalent to manganese from other industries where the manganese is present in a purer form.

3. Calculations show that it is highly unlikely for welders to be exposed to manganese in amounts large enough to cause manganism.

4. In addition, the biological mechanisms of manganese transport across the blood-brain barrier in the presence of iron indicate that manganese in welding fume carries its own antidote, due the fact it is always simultaneously ingested with large amounts of iron. Iron and manganese ingested together have been observed to behave antagonistically.

5. These findings are in agreement with the literature, where there is no direct evidence of any welding related manganism.

6. Welding fume is made up of a complex mixture of elements in the form of compounds, which may lead to difficulties in applying single exposure limits for the individual elements contained in the fume.

7. The evidence suggests that manganese contained in welding fume affects the body in different ways than manganese from other industries, such as manganese mines and foundries. Because of this evidence, the welding industry should not be under the same restrictions, i.e. the ACGIH TLV® - TWA of 0.2 mg/m^3, as the industries where this regulation was developed. OSHA is urged to consider this when reviewing its PEL for manganese. The welding industry should be regulated by exposure limits developed using data from welding activities.

8. The costs of compliance with the ACGIH standard would be unnecessary and should be avoided.

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