IV. HEALTH AND SAFETY HAZARDS

A. Introduction

Welding processes are potentially hazardous because they require intense energy to change the physical state of metals. The chemical changes associated with such energy may result in emissions of various toxic fumes, dusts, gases, and vapors; they may also generate exposures to physical agents that include noise, vibration, heat, electrical current, and infrared (IR), visible, ultraviolet (UV), ionizing, and radiofrequency (RF) radiation.

The degree of risk varies with the method and control measures employed, work practices used, metals and fluxes involved, and duration of exposure permitted. Safety hazards encountered on a daily basis complicate working conditions for welders. These conditions have resulted in both major and minor traumatic injuries and in death.

B. Health Hazards

1. Animal Toxicity

a. Introduction

Over the past 40 years, a number of animal studies have examined the acute and subchronic effects of welding fumes and the mutagenic potential of total airborne welding emissions (gases plus fumes). However, only one animal study has investigated the carcinogenicity of welding fumes as a result of long-term exposures [Reuzel et al. 1986]. In this document, the term "welding emissions" refers to a combination of gases plus fumes. Unless otherwise reported, these exposures were generated from shielded metal arc or gas metal arc welding.

b. Acute Effects

In a series of experiments, Titus et al. [1935] exposed groups of animals (1 to 4 cats, 1 to 5 rabbits) for 0.8 to 8.5 hr to iron oxide or to the welding emissions produced during electric arc cutting of iron with iron electrodes. Exposure concentrations ranged from 10 to 350 mg/m^3 (0.3-μm particle size) of fumes, which contained mostly ferric oxide. Concentrations above 275 mg/m^3 were difficult to maintain, since at these increased concentrations, the particles from the fumes aggregated as rapidly as they were produced. To accentuate the effect of fume exposure, carbon dioxide (1% to 14%) was added to chamber air to increase respiration. An additional four groups of rabbits were exposed to arc cutting gases

alone, and two other groups were exposed to ferric oxide alone at concentrations comparable with those contained in the fumes. When exposed to high concentrations of either the arc cutting emissions (320 mg/m^3) or gases, animals exhibited severe pulmonary edema, dilation of alveoli, hemorrhage of the lungs, and death. Since higher air concentrations of ferric oxide alone did not cause acute lung pathology or death in exposed animals, the arc cutting gases (unidentified) were considered the probable cause of the observed toxicity. The authors noted that these pulmonary effects induced by the gaseous components of the emissions were similar to those caused by such irritating gases as nitrogen peroxide, ozone, or chlorine.

Senczuk [1967] administered 0.5-ml saline suspensions of welding fumes generated from either acid-, basic-, or rutile-coated electrodes into the stomachs of six white female mice (strain unspecified) per treatment group. The type of metal welded was not stated. The suspension from basic electrode fumes produced lethality at lower doses than did suspensions from acid or rutile fumes. The dose capable of killing 50% of the animals within 48 hr after treatment (LD_{50}) was 755, 5,000, or 5,000 mg/kg for suspended fumes generated from basic-, acid-, or rutile-coated electrodes, respectively. When similar suspensions were intratracheally injected into groups of six white female Wistar rats, the LD_{50}'s for basic, acid, or rutile welding fumes were 132, 762, or 792 mg/kg, respectively. Welding fume composition was analytically determined by an unreported method. The author theorized that the increased toxicity associated with basic electrode fumes was caused by fluorine, which was not present in the other test electrode fumes. Manganese, silicon, and aluminum compounds were considered the toxic components of acid or rutile dusts, whereas sodium and magnesium carbonates and titanium compounds were considered much less toxic. Chromium content was neither determined nor discussed.

Kawada and Iwano [1964] used several animal species to study the acute lethality of emissions from basic and rutile (ilmenite) electrode welding of a steel (composition undefined) plate. Unknown strains of mature male mice, white rats, rabbits, and guinea pigs were subjected to a 1-hr inhalation exposure to emissions from a 1-min burn with a basic electrode. The group sizes and chamber emission concentrations were unspecified. Since lethality was observed only in the guinea pig, the guinea pig was chosen as the test species for further study. A 1-hr inhalation of emissions from a 1-min burn of a basic electrode produced death within 24 hr in 10 of 12 guinea pigs and in 2 of 10 guinea pigs when exposure was to rutile emissions under the same conditions. Upon sacrifice of the survivors from the group exposed to basic fumes (time unspecified), the collective histopathology for the lungs revealed deposits of fumes, blood stasis, edema, pneumonia, atelectasis, and emphysema. However, when an additional group of guinea pigs was exposed only to the gaseous components of basic electrode emission, no deaths occurred. The disposition of these animals was not stated.

Kawada and Iwano [1964] also used additional groups of guinea pigs that were intraperitoneally injected with a constant volume of 2 ml of either a water suspension containing 150 mg of basic or rutile fumes or the supernate or insoluble sediment fractions of a similar suspension. The aqueous suspension of basic electrode fumes killed 15 of 15 guinea pigs within 3.5 hr after injection, whereas the suspension of rutile fumes was nonlethal in 6 of 6 treated guinea pigs. Because rutile fumes were not lethal in guinea pigs, no further testing of soluble or insoluble fractions was conducted. Intraperitoneal injection of the water soluble fraction from basic electrode fumes resulted in the deaths of all six treated animals within 1 hr after injection, but six of six animals survived administration of the water-insoluble fraction. Each active compound present in the water-soluble fraction of basic welding fumes was tested and ranked by decreasing lethal potential as follows: potassium fluoride, potassium acid fluoride, potassium hydroxide, sodium hydroxide, sodium fluoride, and calcium silicofluoride. Since the water-insoluble metal oxides (aluminum, barium, calcium, iron, magnesium, manganese, silicon, or titanium) in these two fumes were not lethal to injected animals, the authors did not consider them to be toxicologically active.

Hewitt and Hicks [1973] exposed male albino SCE strain rats by inhalation to rutile welding emissions at an average concentration of 1,500 mg/m^3. The lungs were analyzed with neutron activation to assess tissue concentrations, rates of uptake, and elimination of inhaled metals. Metal uptake in liver and blood was also assessed. The rutile iron electrode used was coated with limestone, manganese dioxide, kaolin, cellulose powder, and sodium and potassium silicate binders. Two rats were exposed for 30 min, while seven rats were exposed for 4 hr. Tissue concentrations at 24-hr post-exposure were expressed as μg compound/g of freeze-dried tissue. The rats exposed for 30 min had a statistically significant increase ($p<0.05$) of iron (1,175 μg) and cobalt (0.22 μg) in the lung but not chromium (0.01 μg) or antimony (0.01 μg) when compared with controls. The seven rats exposed for 4 hr had a statistically significant increase ($p<0.05$) in iron (7,175 μg), cobalt (0.32 μg), chromium (0.03 μg), and antimony (0.25 μg) in the lung. Additionally, the cobalt concentrations in the liver (0.6 μg) and blood (0.2 μg) were statistically increased ($p<0.05$) after a 4-hr exposure when compared to the controls. Microscopic examination of the treated lungs revealed large numbers of particulate-loaded macrophages in the alveoli and alveolar ducts, slight alveolar epithelial thickening, and peribronchial edema. In a subsequent experiment, eight rats were exposed to welding emissions for 4 hr. Pairs of these animals (and pairs of control rats) were killed 1, 7, 28, or 75 days after exposure. The iron, cobalt, chromium, and antimony contents in the lung progressively decreased over the 75-day period.

The histopathological lung changes that were observed within the first 4 hr of exposure returned to normal following 75 days of no exposure. However, macrophages that contained particulate material continued to be present.

c. Subchronic Effects

The effects of welding emissions on animals have been summarized in Table IV-1. Tollman et al. [1941] performed an inhalation study in which 2 groups of 12 young adult guinea pigs and 10 young adult white rats were exposed for 4 hr/day, 6 days/week. One group was exposed for approximately 29 weeks to partially filtered carbon arc welding emissions, and the other group was exposed for approximately 33 weeks to oxides of nitrogen only. This was followed by a 1-month nonexposure period for guinea pigs. The type of metal welded and filter used were not reported. Fumes passing through the filter were less than 25 mg/m^3 during the total study period. The authors reported that the average concentration of oxides of nitrogen was 107 ppm in the gas phase of the welding emissions. This concentration was comparable to the average concentration of oxides of nitrogen (125 ppm) when administered alone. The investigators found a consistent response in all test groups regardless of the parameter studied. Guinea pigs in both groups had an average loss of 11% to 15% in terminal body weights when compared with their maximum weights attained during the experiment. Similar weight loss data for rats were not given. At the end of 7-1/2 months of treatment, guinea pig mortality reached 67% in the filtered emissions group and 92% in the oxides of nitrogen group, whereas all rats were dead within the first 3.4 months of exposure. Histopathologic examination of tissues revealed the lungs as the primary target organ for both species and all treatment groups. Pulmonary pathology included: epithelial desquamation and necrosis, atelectasis, edema, and pneumonia. The principal differences observed were thicker alveolar walls and more macrophages in the lungs of those animals exposed to filtered welding emissions. No histopathology was specifically cited for the guinea pigs that survived the exposure period. The authors concluded that the effects were primarily due to exposure to oxides of nitrogen rather than to any other component present in carbon arc welding emissions.

McCord et al. [1941] reported on the inhalation exposure of 24 albino rats and 16 rabbits of both sexes (strains, ages, and numbers of each sex not given) to the emissions produced during shielded metal arc welding (unspecified metal) from electrodes that contained mostly silicon (21%) and titanium (42%) dioxides. An equal number of nonexposed rats and rabbits were used as controls. Exposures were for 6 hr/day, 5 days/week for a total of 46 days. This was followed by 43 days of nonexposure before study termination. The total fume concentration was not given; however, four components accounted for over 97%: iron oxide (79%), manganese oxide (5%), silicon dioxide (8.4%), and titanium dioxide (5.4%). The average chamber concentration of nitrogen dioxide was 20-24 ppm, and the average nitrous oxide concentration was 3 ppm, while the average concentrations of ferric oxide, manganese, and silicon dioxide were 465, 16, and 61 mg/m^3, respectively. Titanium dioxide values were

Table IV-1.--Summary of animal studies on the effects of welding emissions

Type of metal	Type of welding (electrode)	Toxic agents (total emissions, gases, or fumes)	Species	Route and duration of exposure	Dose(s)	References
Not reported	Carbon arc (carbon)	Partially filtered emissions or oxides of nitrogen	Guinea pigs and rats	Inhalation 4 hr/day x 6 days/week for up to 200 days exposure (plus a 1-month nonexposure period in guinea pigs only)	Partially filtered emissions: oxides of nitrogen, 107 ppm plus fumes, <25 mg/m^3 Gas administered alone: oxides of nitrogen, 125 ppm	Tollman et al. [1941]
	Summary of effects:	Similar effects were induced for the treatment groups of both species: weight loss, lung pathology (epithelial necrosis or desquamation, atelectasis, edema, and pneumonia) and death.				
Not reported	Shielded metal arc (silicon/ titanium dioxides)	Fumes	Rats and rabbits	Inhalation 6 hr/day x 5 days/week for 46 days exposure plus 43 days of recovery	Total fume concentration not given.	McCord et al. [1941]
	Summary of effects:	The treated animals for both test species developed losses in body weights and siderosis (without silicosis). During the nonexposure period the iron concentration in the lungs of treated animals progressively decreased.				

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Table IV-1 (Continued).--Summary of animal studies on the effects of welding emissions

Type of metal	Type of welding (electrode)	Toxic agents (total emissions, gases, or fumes)	Species	Route and duration of exposure	Dose(s)	References
Not reported	Shielded metal arc (basic or rutile)	Emissions	Rats and rabbits	Inhalation 3 hr/day x 7/week for 91-110 days plus 130-182 days of nonexposure	Basic: 60 mg/m^3; Rutile: 198-222 mg/m^3	Byczkowski et al. [1970]
Summary of effects: Rats and rabbits had approximately equal capacities to clear fume metals deposited in trachea and lung. Iron clearance from tissues was still incomplete at end of nonexposure period.						
Mild steel	Shielded metal arc (basic)	Emissions	Rats	Inhalation 1 hr/day x 5 days/week for 1, 2, 3, or 4 weeks with sacrifice 24 hr after last exposure or 1 hr/day x 5 days/week x 4 weeks plus 106 days of nonexposure	Basic or rutile: 43 mg/m^3	Kalliomaki et al. [1983]
Stainless steels	Shielded metal arc (rutile)	Emissions	Rats	Inhalation 1 hr/day x 5 days/week for 1, 2, 3, or 4 weeks with sacrifice 24 hr after last exposure or 1 hr/day x 5 days/week x 4 weeks plus 106 days of nonexposure		
Summary of effects: Both emissions induced metal deposition in the lungs directly proportional to the metal content in the emissions. Slow lung metal clearance times ($T_{1/2}$) were up to 50 days.						

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Table IV-1 (Continued).--Summary of animal studies on the effects of welding emissions

Type of metal	Type of welding (electrode)	Toxic agents (total emissions, gases, or fumes)	Species	Route and duration of exposure	Dose(s)	References
Not reported	Shielded metal arc (rutile)	Emissions	Wistar rats	Inhalation 3 hr/day x 13 weeks plus 26 weeks of recovery	222 mg/m^3	Senczuk [1967]
	Summary of effects:	Exposure to shielded metal arc emissions produced different weight gains in treated and control rats, -2% and +18%, respectively; however, the lung weights were similar. During the nonexposure period, the weight gain in treated and control rats was +2% and +29%, respectively, while treated lung weights were 18% heavier than controls.				
Not reported	Shielded metal arc (high silicon/high iron oxide)	Emissions	Guinea pigs	Inhalation 4 hr/day x 6 days/week for 110 days	High or low silicon: 18-36 mg/m^3	Garnuszewski and Dobrzynski [1966]
	Shielded metal arc (low silicon/high iron oxide)	Emissions	Guinea pigs and rabbits	4 hr/day x 6 days/week x 26 weeks plus 4-mo nonexposure for guinea pigs only		
	Summary of effects:	All treated groups of animals had siderosis. For high silicon oxide electrode emissions the guinea pigs had silicosis and pneumoconiosis of the interalveolar septa which also had nodules containing collagen fibers and silica particles. Exposure of guinea pigs to low silicon oxide electrode emissions induced little silicosis and few small pneumoconiotic nodules that had less collagenous fiber and silica particle contents when compared to a high silica exposure group. Following a 4-month nonexposure period, these pulmonary lesions did not regress. Rabbits exposed to low silicon oxide emissions had only thick interalveolar septa.				

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Table IV-1 (Continued).--Summary of animal studies on the effects of welding emissions

Type of metal	Type of welding (electrode)	Toxic agents (total emissions, gases, or fumes)	Species	Route and duration of exposure	Dose(s)	References
Stainless steel	Shielded metal arc (undefined) Gas metal arc (uncoated wire)	Fume suspensions in saline	Hamsters	Tracheal intubation 1 day/week x 56 plus 44 weeks nonexposure; except 2.0 mg level for shielded fume which was dosed once a week for 25 weeks, then once every 4 weeks for 31 weeks	Shielded metal arc fume: 0.5 or 2.0 mg/inj. Gas metal arc fume: 2.0 mg/inj. Calcium chromate positive control: 0.1 mg/inj. Saline negative control: 0.2 ml/inj.	Reuzel et al. [1986]
	Summary of effects:	Shielded metal arc fumes induced one lung cancer at each dose. No lung cancers were found in the gas metal arc fume or calcium chromate, saline, and historical control groups.				

not cited. Average weight gains for exposed versus nonexposed groups were 272 g versus 366 g for rabbits and 2.9 g versus 32 g for rats. Siderosis of the lungs was the only biologically significant pathology present in all of the exposed animals sacrificed at the end of the experiment, with the earliest detection of siderosis observed in a rat that died after 22 days of exposure. No silicosis was found in any of these animals.

Byczkowski et al. [1970] reported on the metal concentrations in the lungs of 290 rats and 30 rabbits exposed by inhalation to emissions generated during the melting of basic or rutile electrodes. The effect of exercise on the retention of inhaled metals from rutile welding emissions was also studied in rats. Baseline metal concentrations were determined in an unstated number of animals from each treatment group before the start of the exposure period. Groups of young adult male Wistar rats and 1-year-old albino rabbits (group sizes not specified) were exposed to approximately 60 mg/m^3 of basic welding emissions, while a group of rats was exposed to 198-222 mg/m^3 of rutile welding emissions. In addition, one similarly exposed rutile welding group was exercised by being housed in cages that rotated during two of the 3-hr daily exposures. Exposures for the remaining groups were 3 hr/day, 7 days/week for 91 to 95 days for rats and 110 days for rabbits. During the period of time in which the animals were being exposed, an undefined number of surviving animals in each treatment group were withdrawn from exposure for terminal assessment of changes in lung metal content. Final sacrifices occurred 130 days after termination of exposures for rats and rabbits in the basic welding emissions groups and after 182 days for rats in the rutile welding emissions group.

Rats sacrificed after 95 days of exposure to welding emissions from basic electrodes had total lung tissue contents of 0.57 mg fluorine, 4.95 mg manganese, and 223 mg iron. Similarly exposed rabbits sacrificed at the end of 110 days had lower total lung contents of 0.32 mg fluorine, 4.2 mg manganese, and 103 mg iron when compared to the rats. Tracheal tissue concentrations for fluorine in rats and rabbits were five times higher (2.79 mg and 1.76 mg, respectively) than those found in the lung tissue. The groups of rats and rabbits that were exposed to the same basic welding emissions and removed from exposure for 130 days, had up to a 50% decrease in fluorine and iron levels and over an 80% decrease in manganese from those determined after 95 and 110 days. The group of rats exposed to rutile welding emissions had the following total lung metal contents at the end of the 91- to 95- day exposure period: silicon, 0.45 mg; titanium, 0.117 mg; manganese, 0.495 mg; and iron, 9.3 mg. When these values for the rutile exposure group were compared to those in a similarly exposed but exercised group, exercise increased the metal concentrations by approximately 50%. No analysis was performed for lung metal content during the 182 days that followed the termination of exposure. However, unexercised rats withdrawn from rutile fume exposure for 182 days had approximately a 50% decrease in silicon, titanium, and manganese concentrations but only a 23% decrease in iron.

Kalliomaki et al. [1983] exposed adult male Wistar rats (300±15g) to emissions generated from shielded metal arc welding of either mild steel with basic electrodes or stainless steel with rutile electrodes. The purpose of the study was to determine which metals (iron, manganese, chromium, or nickel) contained in the two types of welding emissions were retained by or cleared from the lung. A total of 52 rats in groups of 2 rats or less was used in 14 treatment and 14 control groups. Each treatment group was exposed to 43 mg/m^3 of emissions. Four of the treatment groups were designed to determine retention of metals in animals exposed for 1 hr/day, 5 days/week for 1, 2, 3, or 4 weeks with sacrifice of a treatment group and a control group 24 hr after last exposure. The animals in the remaining 10 groups were exposed for 1 hr/day, 5 days/week for 4 weeks and were evaluated for clearance of metals. Following the last exposure, a treatment group and a control group were sacrificed at the following time intervals: 1, 3, or 8 hr and 1, 4, 8, 14, 28, 56, or 106 days.

Basic electrode welding of mild steel produced emissions that contained 20% iron and 2.8% manganese by weight but only trace amounts of chromium and nickel (remaining fraction unstated). In rats exposed to these emissions, the lung tissue retention rates for iron and manganese each became saturated by the third week of exposure with initial retention rates of 28 and 4 $\mu g/g$ dry lung tissue/hr, respectively. Clearance time was measured as the time required to decrease the tissue load of a metal by 50% ($T_{1/2}$). These metals had fast and slow clearance times for their curves. Fast clearance $T_{1/2}$ times were 6 days for iron and 0.5 days for manganese; slow clearance $T_{1/2}$ times were 35 for iron and 4.3 days for manganese. Because chromium and nickel were present in only trace amounts in mild steel welding fumes, clearance times for these elements were not determined.

Rutile electrode welding of stainless steel produced emissions which contained 4.0% iron, 2.2% manganese, 3.0% chromium, and 0.4% nickel by weight (remaining composition unstated). In rats exposed to these rutile emissions, the retention curves were linear with initial rates of 4.8 (iron), 2.8 (chromium), and 0.3 (nickel) $\mu g/g$ dry lung tissue/hr. The retention of manganese reached saturation after 19 hr of exposure, with an initial retention rate of 1.5 $\mu g/g$ dry lung tissue/hr. Slow clearance $T_{1/2}$ times were 50 days for iron, 40 days for chromium and manganese, and 30 days for nickel. These metals did not have fast clearance times.

Senczuk [1967] used 3-to 4-month-old Wistar rats to study the toxicity of inhaled emissions produced by welding (metal unspecified) with rutile electrodes. A treatment group of 120 male rats was exposed to an average emission concentration of 222 mg/m^3 for 3 hr/day for 13 weeks. The control group consisted of 30 nonexposed young adult male rats. Interim sacrifices within the exposure group occurred after 2, 4, 6, 8, 11, and 13 weeks, and 2 and 5 weeks postexposure. Similar interim sacrifice intervals were used for the control group with the omission of those during

exposure weeks 2, 6, and 11 and postexposure week 2. Twenty-six weeks after cessation of exposure, the remaining survivors (number unstated) were sacrificed. Mortality within the groups was not reported. Analysis of chamber emissions demonstrated concentrations of 102 mg/m^3 ferric oxide, 15.2 mg/m^3 silicon, 9.4 mg/m^3 manganese, 3.5 mg/m^3 titanium dioxide, and 8 mg/m^3 oxides of nitrogen. Examination of the growth curves showed that the exposed rats progressively lost 2% body weight during the 13-week treatment period. During the 5 weeks following the 13-week exposure period, their body weight gain was parallel to that of the controls, after which it began to decrease. Twenty-six weeks after the 13-week exposure period, the animals' terminal body weights were compared with their preexposure weights. The results showed that the treated rats had a 2% gain while the controls had a 29% gain. Lung weights (dry) from treated and control rats were approximately equal at the end of the exposure period; however, the lung weights (dry) of the treated rats sacrificed 26 weeks following the exposure period were 18% heavier than those of the corresponding controls. Because the lungs were desiccated for weighing, histopathologic evaluations were not performed.

Garnuszewski and Dobrzynski [1966] compared the pulmonary effects of inhalation of welding emissions on guinea pigs and rabbits (strain, age, and sex unreported). Two types of electrodes were used to generate the test emissions, but the type of metal welded was not reported. One type, EP52-28p, had high silicon oxide (25.5%) and high ferric oxide (18%) contents, while the other, EP47-28p, had low silicon oxide (7.8%) but high ferric oxide (23%) levels. Comparative pathology of animal tissues was used to determine if exposure to the welding emissions from the low silicon oxide electrode was biologically safer than that from the high silicon oxide electrode.

The first experiment included a total of 72 guinea pigs exposed to high silicon oxide emissions; half of the group was exposed to emission concentrations of 18 mg/m^3, while the other half was exposed to 36 mg/m^3. The emissions were generated from the high silicon oxide electrode and the experiments carried out 4 hr/day, 6 days/week for 110 days. A total of 10 guinea pigs comprised the nonexposed (undefined) control group. Although the number of animal deaths per treatment group was not stated, the combined total was 30 of 72. Guinea pigs exposed to either emission concentration had a mixed type of pneumoconiosis (e.g., siderosis coexisting with silicosis as manifested by pneumoconiotic nodules containing collagenous fibers and silica particles). Phagocytes containing silica and iron oxide particles were found in abundance throughout the trachea, bronchi, and interalveolar septa and lumen. The above findings were all concentration-related in intensity.

In the second experiment, 50 guinea pigs and 10 rabbits were exposed to the emissions from the low silicon oxide electrode. The animals were divided into 2 equal groups and exposed 4 hr/day, 6 days/week for 6 months to the same emission concentrations as in the first

experiment. Scheduled sacrifices occurred after 6 months of exposure followed by 1 and 4 months of nonexposure. The control groups included 10 guinea pigs and 2 rabbits. During exposure, the combined mortality for both guinea pig exposure groups was 25 of 50. These low silicon oxide exposures produced fewer and milder pulmonary effects than those observed in the animals of the high silicon groups for the first experiment. The changes were limited to the alveolar septa and alveoli which were thin and sometimes ruptured. All exposed guinea pigs were found to have siderosis, but little silicosis. If nodules were present, they were small and few in number when compared to those induced by high silicon oxide electrode emissions. These small nodules contained fibroblasts, histiocytes, and cells with low amounts of silicon, but did not contain pronounced amounts of collagenous fibers. Because similar histopathology effects were present in tissues from guinea pigs sacrificed after the nonexposure periods, the induced effects were not considered readily reversible. The exposed rabbits had siderosis including slightly thickened interalveolar septa that had few dust-containing cells. Neither collagenous fiber proliferation, silicotic nodules, nor silica particles were observed in rabbit lung tissues. The authors concluded that the emissions from the low silicon oxide electrode were biologically less hazardous than those from the high silicon oxide electrode.

d. Mutagenicity

Welding emissions from shielded metal arc and gas metal arc welding on mild and stainless steels as well as some of the individual metals contained in the emissions have been tested for their potential to induce adverse mutagenic changes in DNA through use of in vitro (bacterial or cell culture) assays, or in vivo (animal) test systems. In bacterial and cell culture tests, the test agent is added to microbiological or tissue culture media, respectively, while in animal tests the agent is administered to live animals. The in vitro and in vivo tests are used as predictors of a chemical agent's potential to induce cancer through genetic changes in exposed animals or humans.

(1) Mild Steel--Bacterial and Cell Culture Studies

Hedenstedt et al. [1977] found the fumes to be nonmutagenic from basic or rutile electrode for shielded metal arc welding and the solid wire or powder-filled rutile electrode for gas metal arc welding of mild steel. E. coli W3110 (pol A^+) and E. coli p3478 (a pol A^- derivate) and S. typhimurium (TA 100), with and without metabolic activation were used in the study. The weight of fume tested per plate ranged from 100 to 1,250 μg.

Maxild et al. [1978] also found that the fumes from rutile shielded metal arc and gas metal arc welding on mild steel were nonmutagenic in the TA 98 and TA 100 test strains of S. typhimurium with or without metabolic activation. The dry

weight of fume suspended in dimethylsulfoxide (DMSO) solvent and added to each test plate ranged from 0.1 to 8 mg.

Shielded metal arc fume from mild steel welding was also confirmed to be nonmutagenic by Stern et al. [1982] following testing in S. typhimurium TA 100 with and without metabolic activation. The types of electrodes used to generate the fume and the weight of fume tested per plate were not reported.

Niebuhr et al. [1980] collected gas metal arc fume from the welding of mild steel when solid nickel electrodes were used. A modified sister chromatid exchange (SCE) assay was used to detect mutations. The presence of nickel in the welding fume induced increases in SCEs that were directly proportional to the amount of nickel biologically available in the test media. Concentrations of water- or serum-soluble nickel that ranged from 2.5 to 10 μg/ml yielded SCEs that ranged from 7.3 to 9.4/cell compared to a control value of 8.4/cell. Although mild steel welding fumes devoid of nickel and chromium(VI) compounds were inactive in bacterial mutagenesis assays [Hedenstedt et al. 1977; Maxild et al. 1978; Stern et al. 1982], the addition of nickel into the fumes produced a slight increase in mutagenic activity in the SCE assay.

Hansen and Stern [1983] used the baby hamster kidney cell (BHK-21) assay to determine the ability of gas metal arc fumes generated from welding with a pure nickel wire electrode to transform colonies. In addition, pure nickel oxides, water soluble nickel acetate, and water insoluble nickel subsulfide were tested. They found that welding fumes and all the tested nickel compounds transformed the BHK-21 cell line.

(2) Stainless Steel

(a) Bacterial and Cell Culture Studies

Hedenstedt et al. [1977] studied the mutagenic potential of fumes generated during either shielded metal arc welding (rutile electrodes) or gas metal arc (solid wire electrodes) welding of stainless steels in E. coli and S. typhimurium bacterial test systems. E. coli W3110 (pol A^+) and E. coli p3478 (a pol A^- derivate), and S. typhimurium (TA 98 and TA 100 strains) were used. All bacterial test systems were studied with and without a liver microsomal metabolizing system (S-9 mix). Both types of welding fumes were mutagenic in the absence of S-9 mix, regardless of bacterial strain employed; however, at equal plate concentrations shielded metal arc welding fumes were more mutagenic than gas metal arc fumes. In addition, all water soluble fume fractions were mutagenic. The magnitude of these mutagenic effects were proportional to the degree of water solubility of the hexavalent chromium compounds present in the two types of stainless steel welding fumes.

The hexavalent chromium content in shielded metal arc welding fumes was significantly higher (10 to 1000 times) than that present in gas metal arc fumes. In S. typhimurium, metabolic inactivation of the mutagenic effects for shielded metal arc fumes required both S-9 mix plus an NADP generating system. For all bacterial strains tested, similar inactivation of gas metal arc fumes required the S-9 mix alone. The authors suggested that the mutagenic potential for both types of stainless steel welding fumes may have been due to their water soluble hexavalent chromium content. However, if different chromium compounds were present in shielded rather than gas metal arc fumes, it would explain why they had dissimilar metabolic requirements for mutagenic inactivation.

Maxild et al. [1978] investigated the mutagenic potential of stainless steel welding fumes by utilizing TA 98 and TA 100 strains of S. typhimurium with and without metabolic activation. The dry weight of shielded metal arc welding fume suspended in DMSO solvent and added to each test plate ranged from 0.1 to 8 mg. Based on the weight of fumes required to double the mutation frequency in these bacterial strains, with or without a liver microsome metabolizing system (S-9 mix), shielded welding fumes were more mutagenic than gas metal arc fumes. The mutagenic activity was reduced for both types of fumes when S-9 mix was used. Regardless of the state of activation, the number of mutations induced by these fumes was increased in a dose-related manner. The authors stated that the amount of fumes produced by shielded metal arc welding was 3 to 6 times greater than that produced by gas metal arc welding. Fume analyses revealed that the fumes from shielded metal arc welding contained 330 times more soluble chromium (valence state unspecified) than did gas metal arc welding fumes.

The amount of welding fumes required to double the mutation rate of the S. typhimurium TA 100 (LT2) bacterial strain was also studied by Pedersen et al. [1983]. The activity was equalized on the basis of the chromium content of aqueous extracts (assumed to be chromium[VI]) of shielded and gas metal arc welding fume versus a chromium(VI) positive control solution (sodium dichromate). The authors did not define the types of welding electrodes used to generate the fume. They established that 9 μg of water-soluble chromium(VI) in shielded metal arc welding fumes, 5 μg of water-soluble chromium(VI) in gas metal arc fumes, and 10 μg of water-soluble sodium dichromate (chromium[VI]) per plate caused mutations to double. The authors concluded that the mutagenic potential of stainless steel welding fumes can be completely accounted for on the basis of their chromium(VI) content.

Stern et al. [1982] used the S. typhimurium TA 100 assay in dose-response experiments and factorial design studies to show that the mutagenic activity present in welding fumes is caused by its soluble chromium(VI) content. When mutagenic activity was expressed as revertants/mg/plate, shielded metal arc welding fumes were more mutagenic than gas metal arc fumes. However, when it was expressed as specific activity (number revertants/μg soluble chromium(VI)/plate), gas metal arc fumes were the more mutagenic of the two types of fumes. The authors concluded that the soluble chromium(VI) content of gas metal arc fumes could be partially reduced to insoluble chromium(VI), and to chromium(III) when reducing substances (aluminium and magnesium) were present. When compared to gas metal arc fumes, the specific activity of chromium(VI) in shielded metal arc welding fumes was reduced by components unique to these fumes. They also observed that when fumes containing chromium(VI) were suspended in water, chromium(VI) was contained in both the water soluble and insoluble phases; however, only the water soluble phase was mutagenically active. The authors stated that data from experiments with synthetic fumes demonstrated that neither the manganese nor the nickel content of stainless steel welding fumes was mutagenic nor did these metal compounds act in an antagonistic or synergistic manner when in the presence of fumes containing chromium(VI).

Hedenstedt et al. [1977] used mammalian cells--the V-79 Chinese hamster cell assay--to detect the mutagenic potential (6-thioguanine resistance) of stainless steel welding fumes. The water soluble fraction of rutile electrode fumes from stainless steel welding produced a significant increase ($p<.01$) in the number of 6-thioguanine resistant mutants when compared to the negative controls.

Koshi [1979] also used a mammalian cell assay--a pseudo-diploid Chinese Hamster cell line--to investigate the mutagenic effect of shielded metal arc versus gas metal arc welding fumes from mild and stainless steels, respectively. This assay was used to determine the frequencies of SCEs. In addition, Koshi studied the metallic composition of these two types of generated fumes and their solubilities in water and in culture medium.

Koshi [1979] found dose-related increases for SCEs for both shielded and gas metal arc welding fumes; however, it took 50 times more weight for the gas metal arc fumes than for shielded metal arc fumes to produce a doubling of the control background rate (5.3 SCE/cell). The lower potency of gas metal arc fumes was directly proportional to the decreased water solubility of its chromium(VI) component. When the frequency of SCEs/cell was compared for equivalent chromium contents, the authors stated chromic acid, a

chromium(VI) component, was the most active followed by shielded metal arc fumes and then gas metal arc fumes; however, they presented other data which support equal activities also. Since water soluble nickel, manganese, or chromium(III) compounds present in the two types of fumes were mutagenically inactive, the authors concluded that the active mutagen was chromium(VI). The induction of increased chromosome aberrations in the form of chromatid gaps and chromatin exchanges were similarly ascribed to the chromium(VI) content in both types of welding fumes tested.

(b) Animal Studies

Knudsen [1980] performed a mammalian spot test in female mice to detect genetic mutations through changes in hair color. T-stock males (homozygous for four recessive coat-color mutations) were mated with C57BL females (homozygous wild-type for the mutations carried by T-stock males). The pregnant C57BL mice were administered suspensions of shielded metal arc welding fumes from stainless steel or doses of potassium chromate (positive control) containing approximately 0.5 to 1.5 times the chromium(VI) content of the fume fraction tested. The type of electrode used for fume generation was not described. The mice were intraperitoneally injected with the test materials on days 8, 9, and 10 of gestation. The offspring were checked for spots of recessive hair color at the end of 2, 3, 4, and 5 weeks of age. The shielded metal arc welding fumes produced the same number of spots as approximately equivalent doses of chromium(VI). The authors suggested that the positive mutagenic effect induced by shielded metal arc welding fumes was primarily caused by its chromium(VI) content.

e. Carcinogenicity

Reuzel et al. [1986] investigated the toxicity of welding fumes intratracheally instilled into the lungs of hamsters. Fumes were produced either from shielded electrodes used during metal arc welding or from wire metal electrodes used during gas metal arc welding of stainless steel. The welding fumes were collected onto filters. Each of five treatment groups contained 35 male Syrian golden hamsters. Dosage quantities of fumes were suspended in 0.2 ml of saline for intratracheal injection. The treatment concentrations were 0.5 and 2.0 mg for two shielded welding groups, 2.0 mg for one gas metal arc welding group, 0.1 mg calcium chromate for a "positive control" group (calcium chromate has not been shown to be carcinogenic in this test system), and 0.2 ml of saline for the unexposed control group. The treatment groups were dosed once weekly for 56 weeks, except that the 2.0 mg shielded welding group developed early body weight loss and a few hamsters died; therefore, from weeks 26 through 56, single doses were injected only on every fourth week. Autopsies for all groups were performed after 100

experimental weeks. The chromium contents of the fume from shielded metal arc and gas metal arc welding fumes were 5% and 0.4%, respectively. The nickel content in shielded metal arc fumes was 0.4% while that for gas metal arc fumes was 2.4%. Although not stated by the authors, the total amount (mg/hamster) of chromium injected during the study was calculated as 1.4 (low dose) and 3.3 (high dose) for the shielded metal arc welding fume groups; 0.45 (low dose) and 5.6 (high dose) for the gas metal arc fume groups, and 1.85 for the calcium chromate positive controls.

Although lung weights of hamsters treated with either 2 mg shielded metal arc fumes or 2 mg gas metal arc fumes were significantly heavier (level unstated) than control lung weights; the heaviest lung weights occurred in the gas metal arc fume group. Regardless of treatment or dose level, hamsters that died and those that survived through the nonexposure period following treatment differed little in histopathology or in the number of dust particles present in lungs. This indicated that little recovery had occurred during this period. However, those hamsters in the 2 mg treatment group exposed to gas metal arc welding fumes had the greatest degree of induced pulmonary pathology. This included moderate to severe nonspecific pneumonia, slight to moderate interstitial pneumonia, moderate alveolar bronchiolization, and slight emphysema. Animals dosed with 0.5 mg shielded metal arc welding fumes and those that received calcium chromate showed similar but less pronounced changes.

Two lung cancers were found in the shielded metal arc welding treatment groups. One cancer (a well-differentiated combined epidermoid and adenocarcinoma type) was found in the lung of an animal that was treated with 2.0 mg of shielded metal arc fumes and sacrificed at the end of the 100-week study. The second cancer (an anaplastic tumor, probably a carcinoma, which had metastasized to the surrounding lung parenchyma and mediastinum) was found in the lung of a hamster that died after one year of treatment with 0.5 mg of shielded metal arc fumes. The investigators believed these two tumors were induced by the shielded metal arc welding fumes and were toxicologically significant because neither noncancerous nor cancerous tumors had been observed either in the concurrent controls or in nearly 800 historical laboratory controls. Because pulmonary tumors were not present in the positive control (calcium chromate) animals, the investigators theorized that compounds other than chromium in welding fumes were probably responsible for the induction of the cancers in the shielded metal arc welding fume groups.

f. Summary--Animal Toxicity

Shielded metal arc welding fumes and gases have caused severe acute lung damage (e.g., edema, hemorrhage, pneumonia, and atelectasis) [Titus et al. 1935; Kawada and Iwano 1964; Hewitt and Hicks 1973]. Basic electrode welding of nonstainless steels that did not contain chromium or nickel has produced fumes that are potentially more lethal than those produced by welding of the same metal with acid or

rutile electrodes [Senczuk 1967]. It appears that the increased toxic potential of the fumes generated while welding with basic electrodes can be ascribed to the high fluoride content that is absent in either acid or rutile-type electrodes.

Subacute toxicologic studies have demonstrated that irreversible chronic lung disease can result in animals repeatedly exposed by inhalation to welding fumes and gases. Tollman et al. [1941] investigated the pulmonary effects in animals repeatedly exposed to welding gases (oxides of nitrogen). Concentrations which induced mortality also caused lung tissue damage (edema, atelectasis, pneumonia, and necrosis). In addition, the subacute effects of total welding emissions (gases plus fumes) generated during the welding of nonstainless steels were studied in animals by Garnuszewski and Dobrzynski [1966] and Senczuk [1967]. In general, these investigators found that exposure of animals to welding emissions induced premature mortality, suppression of weight gain, fibrotic lung disease, and pneumoconiosis in surviving animals. Siderosis and silicosis resulted from exposures to emissions which contained iron or silicon, respectively. This fibrotic pulmonary pathology was found irreversible during nonexposed periods despite recovery times that sometimes exceeded the length of treatment.

Pulmonary deposition and clearance rates for metals contained in emissions generated during the welding of nonstainless and stainless steels were investigated in animals by several authors (McCord et al. 1941, Byczkowski et al. 1970; Kalliomaki et al. 1983). They found the rates of metal deposition in exposed lungs to be proportional to the metal contents in the emissions. These deposition rates were further increased in animals with concomitant exercise during exposure. For some metals with slow clearance rates, even prolonged periods of nonexposure did not permit complete elimination.

In a wide variety of in vitro and in vivo mutagenesis assays, mild steel welding fumes had little to no mutagenic potential, whereas stainless steel welding fumes were consistently mutagenic.

Shielded metal arc welding of stainless steel produced three to six times more fumes "per mass of weld metal" than gas metal arc welding. The shielded metal arc welding fumes were more water soluble than the gas metal arc welding fumes [Maxild et al. 1978]. The water-soluble fraction of these fumes was shown to be mutagenically active [Hedenstedt et al. 1977; Koshi 1979; Stern et al. 1982; Pedersen et al. 1983], but the water-insoluble fraction had no significant mutagenic activity [Stern et al. 1982]. Assays have demonstrated that much of the mutagenic activity may be ascribed to the chromium(VI) in the water-soluble fraction [Stern et al. 1982]. However, when the mutagenic potentials for these fumes were compared on an equivalent chromium(VI) basis, gas metal arc welding fumes produced four times more mutations in bacteria than did shielded metal arc welding fumes [Stern et al. 1982]. Yet SCE data were equivocal for these two types of fumes [Koshi 1979].

In addition, it appears that compounds other than chromium(VI) could also be active in the water soluble fractions of fumes generated from the two welding processes. This is based on the fact that when the water soluble fractions of both fumes were tested in a metabolically activated S. typhimurium mutagenicity assay, only shielded metal arc fumes lost their metabolic potency [Hedenstedt et al. 1977; Stern et al. 1982].

One 2-year carcinogenicity study has been reported for Syrian golden hamsters that were intratracheally injected with saline suspensions of stainless steel welding fumes [Reuzel et al. 1986]. Lung cancer was observed in one animal from each of the two dose groups that were intratracheally injected with shielded metal arc welding fumes. No cancers were observed in the gas metal arc fume treatment group or the calcium chromate, saline, and historical control groups. Despite the fact that there were only two cancers observed, the authors concluded that these tumors were biologically significant based on the absence of tumors in the calcium chromate (positive control) group and the concurrent and historical nonexposed control groups. However, some question exists concerning calcium chromate being considered as a positive control since: (1) no published experimental data shows the induction of any kind of cancers in hamsters when calcium chromate is intratracheally administered, and (2) the number of animals and dose used for the calcium chromate positive control group may not have been large enough to detect a positive carcinogenic response in these animals.

2. Human Toxicity

a. Pulmonary Effects

This section evaluates case reports and epidemiologic studies that document the adverse respiratory effects reported for workers who are associated with various types of welding processes. The studies are presented in order of the severity of the effects they report, beginning with those that discuss the acute effects associated with exposure to welding fumes and gases (e.g., metal fume fever and pneumonitis) and ending with studies that suggest a risk of respiratory cancer. The data from these investigations are summarized in Tables IV-2, IV-3, and IV-4. Although many of the studies have shortcomings (e.g., the absence of information on types and concentrations of specific chemical agents or on smoking habits), they collectively demonstrate the consistency of the many respiratory diseases in welders.

(1) Nonmalignant Pulmonary Diseases

(a) Metal Fume Fever

Metal fume fever is an acute respiratory disease that is usually of short duration; it is caused by the inhalation of metal oxide fumes that are typically 0.2 to 1.0 μm in particle size (Papp 1968). Although several metals are