Effects of Welding on Health, IX

American Welding Society

Key Words — Welding, health, cancer, disease, exposure, fumes, gases, literature review, noise, radiation, toxicology

Effects of Welding on Health IX

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Abstract

This literature review, with 232 citations, was prepared under contract to the American Welding Society for its Safety and Health Committee. The review deals with studies of the fumes, gases radiation, and noise generated during various arc welding processes. Section 1 summarizes recent studies of occupational exposures, Section 2 contains information related to the human health effects, and Section 3 discusses the effects of welding on animals and cell cultures.

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Foreword

(This Foreword is not a part of *Effects of Welding on Health IX,* but is included for information purposes only.)

This literature review was prepared for the Safety and Health Committee of the American Welding Society to provide an assessment of current information concerning the effects of welding on health, as well as to aid in the formulation and design of research projects in this area, as part of an on going program sponsored by the Committee. Previous work consists of the reports Effects of Welding on Health I through VIII each covering approximately 18 months to two years. Conclusions based on this review and recommendations for further research are presented in the introductory portions of the report. Referenced materials are available from:

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Comparative Listing — Welding Processes

Explanatory Note: Terms used in the technical literature sometimes do not correspond to those recommended by AWS in its publication ANSI/AWS A3.0, *Standard Welding Terms and Definitions*.

Accordingly, the following list may aid the reader in identifying the process in use.

EWH — IX		Preferred AWS Term
Gas or Flame Cutting	(OC)	Oxygen Cutting or (OFC) Oxyfuel Gas Cutting
Gas Welding	(OFW)	Oxyfuel Gas Welding or (OAW) Oxyacetylene Welding
MAG	(GMAW)	— (with specified shielding gas)
MIG, GMA	(GMAW)	Gas Metal Arc Welding
MMA, SMA	(SMAW)	Shielded Metal Arc Welding
TIG	(GTAW)	Gas Tungsten Arc Welding
Wire		Electrode

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Many other organizations have also made contributions to support the ongoing program from May 1979 to the present.

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Introduction

Protecting the health of workers in the welding environment is a major concern of the American Welding Society. To stay abreast of this subject, the health literature is periodically reviewed and published in the report Effects of Welding on Health. Eight volumes have been published to date; the first covered data published before 1978, while the latter seven covered time periods between 1978 and December 1989. The current report includes information published between January 1990 and December, 1991. It should be read in conjunction with the previous volumes for a comprehensive treatment of the literature on the Effects of Welding on Health.

Included in this volume are studies of the characteristics of welding emissions that may have an impact on the control technologies necessary to protect the welder (Section 1). In keeping with previous volumes, the health studies are organized according to the affected organ system. The respiratory tract, the primary route of exposure to welding emissions, is also a major target organ of a number of components of these emissions. Acute (e.g., metal fume fever, cadmium poisoning) as well as potential chronic respiratory effects (e.g., bronchitis, cancer) of welding emissions are of concern. Chronic effects on other systems such as the urogenital tract have also been studied. One such effect, injury of the kidney tubules, is known to result from chronic exposure to cadmium. The effect of welding on fertility has received recent attention, but the evidence for a negative impact of welding on fertility is weak and, at the most, uncertain. Continued research in the form of epidemiologic studies, investigations with laboratory animals, and *in vitro* cell studies will help to resolve these questions.

Executive Summary

The Respiratory Tract

The contribution of welding to the development of pulmonary function deficits and respiratory disorders such as bronchitis and asthma remains uncertain, and conflicting results have been reported by different investigators. In studies which have identified a positive relationship between welding and respiratory disorders, it has not been possible to identify specific components of the exposure responsible for these conditions.

Chinn et al. (Ref. 48) and Bogadi-Sare (Ref. 31) found a statistically significant decrease in ventilatory parameters indicative of bronchial obstruction in welders. These results were in accord with those of Kilburn et al. (Refs. 111, 112) who found that reductions in lung function in welders were small, but statistically significant. Lukac et al. (Ref. 128) also found decreases in FEV_1 and FEV_1/FVC among welders, especially among those who smoked. However, non-welding controls were not examined in that study.

In contrast to these results, Melbostad and Ruud (Ref. 136), in their study of metal and machine workers, and Demers et al. (Ref. 53), in their study of boilermakers, found no association between welding and deficits in FVC or FEV_1. Rossignol et al. (Ref. 176) actually found an increase in FEV_1/FVC in experienced welders.

Inconsistent results also were seen among studies of respiratory symptoms. While chronic bronchitis was shown to be significantly related to smoking (Ref. 48), Chinn et al. (Ref. 48) and Bogadi-Sare (Ref. 31) found that it was not related to trade as a welder. However, Kilburn and Warshaw (Refs. 111 and 112) found that nearly 20% of electric arc welders had chronic bronchitis, and the incidence of this disease was related to welding, especially in nonsmokers. In other studies, welders were found to have a high incidence of chronic bronchitis (Refs. 126 and 128). Kleiner et al. (Ref. 115) found that welders developed chronic bronchitis at an earlier age and after briefer employment than mechanics. This effect was much greater in smokers than in non-smokers. Other respiratory symptoms that were studied among welders included asthma and dyspnea. Chinn et al. (Ref. 48) and Bogadi-Sare (Ref. 31) found that breathlessness on exertion was significantly more frequent among welders. Welding was also found to be significantly associated with asthma (Ref. 11).

Cancer

The International Agency for Research on Cancer (IARC) evaluated epidemiologic studies reported through 1989 which assessed the incidence of cancer in welders (Ref. 100) and concluded that "there is *limited* evidence in humans for the carcinogenicity of welding fumes and gases." This evaluation indicates that a "positive association has been observed between exposure to [welding fumes] and cancer for which a causal interpretation is considered...to be credible, but chance, bias, or confounding could not be ruled out with reasonable confidence." The evidence for carcinogenicity in experimental animals was judged to be *inadequate* and the overall evaluation of IARC was that "welding fumes *are possibly carcinogenic to humans.*"

Eleven cohort and twelve case-control studies were considered by IARC in their evaluation of the cancer risk of welders. While most of the cohort studies showed a greater incidence of lung cancer among welders than among control populations, only one of these was significant (Ref. 186). Six of the case-control studies examined by IARC showed greater than a 100% excess lung risk. The excess risk was statistically significant in four of the latter studies. These four studies, served in part as the basis for the conclusion by IARC that there is limited evidence for the carcinogenicity of welding emissions in humans. Also considered by IARC was the positive association of lung cancer with exposure to welding fumes that was seen in an analysis of data pooled from 21 case-control and 27 cohort studies conducted between 1985 and 1989. The results of that analysis were published in 1991 by Simonato et al. (Ref. 184). In this large multinational investigation, the combined study population consisted of 11,092 welders from 135 companies in 9 countries. Of the major causes of death, only those from malignant neoplasms were higher than expected, based on comparison with control populations. This excess was of borderline significance, and was due primarily to a significant excess of deaths from lung cancer (SMR = 134). The risk of death from lung cancer was higher in "mild steel only welders" (SMR = 178) than in "stainless steel ever welders" (SMR = 128). A statistically significant excess of bladder cancer was also observed (SMR = 191). The lung cancer incidence tended to increase with time since first exposure for the "predominantly stainless steel" group. This trend was not significant for any other group of welders. Estimated cumulative doses of total fume, total chromium, or hexavalent chromium were not significantly associated with mortality from lung cancer. The conclusions of this study were confounded by the presence of five cases of mesothelioma, indicative of asbestos exposure, in the cohort of welders. In addition, the effects of tobacco smoking could not be ruled out.

Four new epidemiologic studies of the association between cancer and welders were reported in 1991. Two of these found no cancer excesses compared with the general population (Refs. 25 and 192) and the other two studies showed an excess lung cancer incidence among welders (Refs. 69 and 178).

Fertility

Bonde conducted a series of studies concerned with the fertility of welders. In a case-control study, he showed an increased risk for subfertility (delayed conception) among 432 male welders compared with 240 nonwelding metal workers and electricians (Ref. 32). In a cohort study, Bonde et al. (Ref. 35) showed that among persons who had ever worked as welders, the probability of having a child was slightly, but significantly, reduced during the year following a year of welding exposure. The reduction in fertility was associated with the welding of mild steel, but not with SMAW or GTAW of stainless steel. Changes in sperm quality and follicle stimulating hormone were found in 35 stainless steel welders and also in 46 mild steel welders compared with 54 nonwelding metalworkers (Ref. 33). The effects were most marked among mild steel welders. Changes in semen quality were not found to be reversible, as semen quality did not improve during a 3-week welding-free vacation period (Ref. 34).

While Bonde's studies suggest a reduction in fertility and semen quality with welding, the changes observed were slight, albeit significant. A positive dose-response was not obtained when fertility was considered in terms of years of welding exposure. Nonwelders were excluded from the large cohort study (Ref. 35) because their fertility rate was lower than that of welders during periods of nonexposure. The rationale for excluding nonwelders from the study is not clear, and it is possible that a direct comparison between the overall fertility rates among welders (including periods of both welding and nonwelding) and nonwelders would have shown no difference between the two groups.

Bonde's conclusion that welding reduces fertility was based on differences in birthrates between periods of welding and nonwelding in the same group of welders. However, differences in the fertility of welders between periods of welding and nonwelding could have been due to factors other than welding, and a more valid comparison would be between men who were never welders and those who worked continuously as welders during their entire family-raising period. Finally, while the investigation of semen quality supported the concept that welding is associated with decreased fertility, there were some inconsistencies between the findings of the fertility and semen quality studies. As Bonde pointed out, the observed changes were small and thus subject to confounding factors which are impossible to control with human populations. Because the effects are small, controlled studies in laboratory animals may be necessary to resolve questions concerning the effects of welding exposures on fertility.

One animal study published during this report period examined the effects of chromium on male genitalia (Ref. 63). In that study, hexavalent chromium, but not trivalent chromium caused a reduction in testicular weight, a dose-dependent increase in the number of atrophic seminiferous tubules, and a reduction in the epididymal sperm count. This study is not directly relevant to fertility in welders because the route of exposure was intraperitoneal injection, the effects of which can vary markedly from those caused by inhalation.

Chromium

An important area of research involves the effects of long-term exposure to low levels of chromium. This pursuit has captured the attention of investigators concerned with industrial exposures such as welding (Ref. 36 and 219) as well as environmental exposures (Ref. 41). Drawing from the known effects of acute exposure to high concentrations of chromium on the kidney, Wedeen and Qian (Ref. 219) conjectured that long-term exposure to low levels of chromium could cause kidney tubular disease. Based on the fertility studies discussed above, Bonde postulated that long-term exposure to low levels of chromium could reduce fertility in welders. In regard to this issue, Bonde and Christensen (Ref. 36) determined chromium levels in body fluids from welders working with processes that generate fumes containing low concentrations of chromate. Chromium concentrations were significantly higher in blood and urine from stainless steel and mild steel welders than from controls. However, the concentrations of chromium in blood and urine did not change across a workshift or after a 3-week vacation break from welding. The authors found these data to be consistent with a gradual buildup of chromium in the body during long-term welding exposure. While high concentrations of chromium were found in seminal fluid from welders conducting SMAW of stainless steel, the extremely wide variation in chromium levels indicated that much of the chromium may have been derived from nonoccupational activities.

Because studies in which effects are low and difficult to detect are easily confounded by external factors unrelated to occupational exposures, it is important to be aware of nonvocational factors that could introduce error into epidemiologic studies. As part of their studies of biological monitoring of New Jersey state workers with low-level intermittent exposures to chromium in soil, Bukowski et al. (Ref. 41) determined the contribution of avocational activities and personal habits to urinary chromium levels. They showed that males had slightly higher urinary chromium levels than did females. Beer drinking was associated with a significant increase in urinary chromium. Subjects who used tobacco, and those who had exercised within 24 hours before sampling, had slightly lower chromium levels in the urine. Neither welding nor engaging in hobby activities with possible chromium exposures was associated with increased concentrations of chromium in the urine or blood.

Coogan et al. (Ref. 50) demonstrated that lymphocytes can serve as a better biomarker than red blood cells for long-term chromium exposure. They showed that white blood cells can accumulate significantly more chromium than red blood cells. While the chromium uptake by red blood cells appeared to be independent of the valence state of the administered chromium, lymphocytes accumulated only hexavalent chromium. The investigators concluded that the exclusive accumulation of hexavalent chromium by white blood cells supports their use as target cells in the development of biomarkers for assessing exposure to chromium.

Technical Summary

The Exposure

Fumes

Using a model developed to predict the composition of welding fumes generated by SMAW and FCAW, Hewitt and Hirst (Ref. 87) showed that the flux contributes disproportionately to the mass of the fume based upon its share of the total weight of the wire. Hilton and Plumridge (Ref. 91) demonstrated that gas metal arc welding (GMAW) of stainless steel with a carbon dioxide shielding gas or stainless steel with helium as the shielding gas produced much more fumes than did GMAW with argon-based shielding gases.

When welding aluminum alloys at currents above 150 A, the FGR from an alloy containing 5% magnesium was much greater than that from a 5% silicon alloy. Chromium, nickel, manganese, and fluoride were the components most often measured in several studies of the hazardous components of welding fumes. The hazardous fume component that was most likely to reach the permissible exposure limits (PEL) during welding of stainless steel was hexavalent chromium [Cr(VI)] (Refs. 152, 194, 213, and 230).

Sutton (Ref. 194) showed that Cr(VI) produced by GMAW and gas tungsten arc welding (GTAW) of stainless steel was much lower than that from shielded metal arc welding (SMAW) of the same material. However, Olah and Pospisilova (Ref. 152) found that even though total fume production from GMAW is less than that from SMAW using electrodes with a high-chromium content, the chromium concentration in the GMAW fumes was so much higher that chromium emissions were about equal for the two processes. Although GTAW fumes contained up to 21% chromium, GTAW produced the lowest emission rate for chromium of all the methods tested. Zaks (Ref. 229) showed that manganese (from acid coatings) and fluoride (from basic coatings) were the fume components most likely to reach hazardous levels from SMAW of mild steel.

GMAW of steel coated with tin or zinc produced more fumes than welding aluminum-coated or uncoated steel (Ref. 135). Medack and Heinze (Ref. 135) calculated that air concentrations of zinc released when welding zinc-coated steel, would approach the PEL before any of the other components of the fume. Lead would be the comparable limiting factor from welding tin-coated steel. In fumes from welding aluminum-coated or uncoated steel, manganese from the electrode was the limiting factor.

Analytical Techniques. A particle-sizing method used by Ukkonen et al. (Ref. 206), combining a photometer and an electric particle counter, worked well for sizing particles with unit density but not for the denser particles of welding fumes. Battistoni et al. (Ref. 17) used a photometer to measure particle concentrations from GMAW with a continuous automatic welder. Goschnick et al. (Ref. 80) used secondary neutral mass spectrometry to measure the compositions of successive layers of welding particles. Chromium was enriched in the fume particles compared to its concentration in the electrodes. Contrary to findings of other investigators (Refs. 81 and 129), the chemical composition of the outer and inner layers of the particles did not vary.

Lasers

Lasers used for welding are usually class IV, the most hazardous rating, and require safety features to prevent exposure. Ordinary welding curtains are not suitable for protection against the energy of the laser beam, and special laser barriers must be used. A useful feature that can be incorporated into these barriers is a surface coating that shows visual signs of exposure to stray laser beams (Ref. 221). The electrical power supplies and the chemicals used with lasers also present hazards in the workplace, as do the fumes generated by welding with lasers (Ref. 109). Engel et al. (Ref. 60) found that more fumes were released while cutting stainless steel with CO_2 lasers than while cutting nonalloyed steel. The fume particles were spheres and agglomerates of spheres of submicrometer size, and their composition was similar to that of the metal being cut.

Electromagnetic Fields

Electromagnetic fields (EMFs) are produced by the power sources used in all types of electric arc welding. Although it is not clear that EMFs from welding pose a health hazard, it has been suggested by Zyubanova et al. (Ref. 232) that their intensity may be diminished by the use of coaxial cable to minimize the distance between the electric power lines.

Incidental Exposures

Henriks-Eckerman et al. (Ref. 84) developed a sampling procedure for monitoring workplace pollutants arising from production coatings on the metal surface. The procedure, which included a chemosorbent tube for aldehydes and a tube of adsorbent resin preceded by a glass fiber filter for particulates and condensable organic chemicals, was used to monitor the exposure of metal workers to paint degradation products generated by welding, flame cutting, and straightening painted steels in a Finnish shipyard (Ref. 61).

Onodera et al. (Ref. 157) measured emissions of radioactivity during the decommissioning of a Japanese nuclear power plant. Generally, cutting with a welding torch produced less radioactivity than cutting with mechanical tools. Cutting under water reduced radioactive emissions to an even greater extent. Carmichael and Haynes (Ref. 46) described safety practices and exposure measurements during repairs to apparatus contaminated with tritium at a Canadian nuclear power plant.

Hygiene and Work Practices

Equipment. Using computer simulations and laboratory data, Tum Suden et al. (Ref. 205) showed that the parameters of hood design and operation that affected breathing zone concentration are flow rate through the hood, hood aspect ratio, and the welder's position relative to the hood. Jakubcik (Ref. 102) reported that ventilation was improved during tack-welding of long pieces by enclosing the work in a segmented hood which could be opened in the area where the work was being performed. For gun-mounted fume collection devices, the position of the exhaust vents is important in determining collection efficiency (Ref. 51). A welding table designed by van der Veen and Regensburg (Ref. 210) combined efficient ventilation, absorption of ultraviolet (UV) radiation, and height adjustments to prevent muscular stress.

Protective Gear. Two devices employing activated carbon filtration were shown to be effective in reducing ozone concentrations in the breathing zone (Ref. 193). Several types of material were found to provide superior heat protection to asbestos, but some of the flame-proof clothing tested lost resistance to ignition after 10 or 20 washings (Ref. 105).

Accidents. Analysis of accidents fatal to welders showed that the welding apparatus was not often implicated. Most of the fatal accidents analyzed by Trent and Wyant (Ref. 203) were due to welders falling or being struck by falling objects and to environmental hazards in the workplace. Three fatal accidents involving falls were described by the National Institute of Occupational Safety and Health in 1990 and 1991 (Refs. 146-148). Rekus (Ref. 169) reviewed several cases of fatal accidents to workers entering confined spaces. Tanks and holds that have been recently opened after having been sealed for long periods are particularly hazardous due to accumulation of toxic gases or depletion of oxygen.

Stress. Physiological stresses to welders were documented in two studies in 1990 and 1991. Valente and Chiapperini (Ref. 209) and Richter (Ref. 170) measured pulse rate, blood pressure, oral and skin temperature, and perspiration rate in four welders and related the results to working conditions. Psychological stresses among welders were attributed by Richter (Ref. 170) and Hyytiainen and Uutela (Ref. 97) to the tediousness of the work, the constant need for exercising caution, and the isolation of the worker in the welding environment. Gerhardsson (Ref. 75) found that welders reported a combination of high work load and little opportunity to influence the work situation, which has been related to some physical manifestations of stress.

The Effects of Welding on Human Health

Respiratory Tract

Pulmonary Function and Bronchitis. Welders were included in seven studies of lung function and respiratory symptoms. Chinn et al. (Ref. 48) found significant associations between trade as a welder and development of breathlessness upon minimal exertion. A decline in the lung function parameter FEV_1 was related to occupation as a welder or caulker/burner and to atopy (positive response to skin tests with common allergens).

Bogadi-Sare (Ref. 31) found a significant decrease in FEV_1 and FEV_1/FVC among 47 stainless steel welders and 59 nonwelders employed in machining and polishing stainless steel. The frequency of chronic bronchitis was the same in exposed and unexposed workers, but the exposed group had significantly more frequent complaints of dyspnea and choking. In a community study which included 84 welders, Bakke et al. (Ref. 10) found welding to be significantly related to chronic obstructive lung disease and asthma.

Kilburn and Warshaw (Ref. 111) found small, but significant deficits in FEV_1, FEF_{25-75}, and FEF_{75-85} in 291 male welders compared with historical controls from the same geographical area. In a second study, Kilburn et al. (Ref. 112) found that the rate of chronic bronchitis was substantially elevated in gas tungsten arc welders and was unrelated to smoking. There was a small but significant reduction in FVC, FEV_1, and FEF_{25-75} in smoking welders compared to the reference population while only the FEF_{25-75} was reduced in nonsmoking welders. Further tests showed that changes in lung function do not occur during a workshift in workers exposed to stainless steel welding fumes.

Lukac et al. (Ref. 128) found deficits in FEV_1 and FEV_1/FVC that were related to duration of exposure in welders of steel bridge components. This study did not have nonwelding controls. Melbostad and Ruud (Ref. 136) found no difference in lung function (FEV_1/FVC) between welders and machinists, but work-related respiratory symptoms were more prominent among welders. Contrary to the findings of most other studies, Rossignol et al. (Ref. 176) found a significant increase in FEV_1/FVC with length of employment as a welder or burner.

Kleiner et al. (Ref. 115) found significantly more chronic bronchitis among welders (24.3%) than among mechanics. Demers et al. (Ref. 53) studied asbestos-exposed boilermakers and did not find a positive relation between welding and respiratory disease or changes in lung function. Lubianova et al. (Ref. 127) found a 35% incidence of signs of chronic bronchitis among welders, related to years of exposure, age, and smoking.

Case Reports. Three of the 35 cases of occupational asthma reported to the Ministry of Labor in Singapore between 1983 and 1990 were welders. The prevalence of smoking and the percentage who reacted positively to environmental allergen skin prick testing were not significantly different from controls (Ref. 121).

Lasfargues et al. (Ref. 120) described a case of siderosis and interstitial fibrosis in a man who had welded for 30 years. Wagner et al. (Ref. 217) described post mortem findings of pneumonoconioses, chronic tracheobronchitis, and massive emphysema in the lungs of a man who had worked as an arc welder for 15 years. Chemical analysis of his lung tissue revealed excessive concentrations of iron, aluminum, chromium, nickel, manganese, and copper. Pneumoconiosis and asbestosis lesions in the lungs of a welder examined by Kishimoto et al. (Ref. 113) were considered to provide an ideal culture medium for a Mycobacterial infection which was present in the patient's lung.

Cancer

Lung Cancer. The International Agency for Research on Cancer (IARC) concluded that welding fumes are possibly carcinogenic to humans, based upon limited evidence in humans and inadequate evidence in experimental animals (Ref. 100). Included in the data considered by IARC was the analysis of a pool of 21 case-control studies and 27 cohort studies published in 1991 by Simonato et al. (Ref. 184). That analysis showed a significant excess of lung cancers (Standard mortality ratio: SMR = 134) among welders.

Four new epidemiologic studies of the association between cancer and welders were reported in 1991. Becker et al. (Ref. 25) found a significant excess of deaths from all malignancies among welders when compared with machinists in the same plant in the Federal Republic of Germany (Relative risk = 1.6). However, welders did not have a significantly elevated risk of lung cancer when compared to the general population. In an American study (Ref. 192), limited to mild steel welders who had no asbestos exposure, lung cancer was not associated with welding when welders were compared with either the general population or to nonwelders in the same plants. Analysis of cancer registry data (1971 to 1980) in Finland found a statistically significant increased risk for lung cancer among welders (Standardized Incidence Ratio = 150) (Ref. 178). Similarly, the 125 lung cancer deaths of welders in British Columbia between 1950 and 1984 were significantly greater than expected (Proportional Mortality Ratio = 129), compared with the general population and to a subgroup of skilled manual workers. Significantly greater risks were also found for Hodgkin's disease and all cancers in that study (Ref. 69).

Cancer at Other Sites. Ahrens et al. (Ref. 2) found that nasal and laryngeal cancer were strongly linked to smoking and alcohol consumption but not to welding. Yu et al. (Ref. 227) identified exposure to combustion products among risk factors for nasopharyngeal carcinomas. In this exposure group, 15 cases and eight controls were exposed to welding fumes, but the significance of these numbers was not reported. Bladder cancer was found to be significantly elevated in the combined study population analyzed by Simonato et al. (Ref. 184), but the incidence of cancer was unrelated to duration or intensity of exposure.

Cancer in Children of Welders. A heritable form of retinoblastoma, a tumor in the retina occurring in young children, was linked to father's occupation in the metal-working industry. The nonheritable form of the disease, believed to be the result of post-conception exposures, was linked to fathers working in a job cluster that included welders, machinists, and paper-processing workers (Ref. 43). Welders were not analyzed separately in either study so that the contribution of welding exposures to this disease cannot be assessed.

Cancers Associated with Electromagnetic Fields. Five epidemiological studies of the incidence of leukemias and cancer of the central nervous system reported in 1990 and 1991 included welders in the exposed population. Leukemia was linked to exposure to electromagnetic fields (EMFs), but not to welding, in three studies, (Refs. 16, 106 and 201) and no relationship was found between the risk of leukemia and exposure to EMFs in the second study (Ref. 158). EMF exposure was implicated in central nervous system cancer in three studies (Refs. 68, 106 and 201). Although the data for welders were analyzed separately in all three studies, only one indicated a link between welding and central nervous system cancer, and that was of borderline significance (Ref. 201).

Cancers Associated with Ultraviolet Radiation. Holly et al. (Ref. 93) conducted a case-control study of the association between uveal melanoma and exposure to UV light. A statistically significant relative risk for uveal melanoma was found among persons included in a group who had experienced welding burn, sunburn of the eye, or snow blindness.

Metal Fume Fever

A typical case of metal fume fever was described by Heydon and Kagan (Ref. 88). The patient developed a cough, chills, cramps, and difficulty breathing 2 hours after cutting galvanized steel with a gas torch without using a mask.

Based on the hypothesis that polymorphonuclear leukocytes (PMNs) responding to inhaled zinc oxide fumes release mediators (cytokines) that can elicit the systemic effects characteristic of metal fume fever, Blanc et al. (Ref. 27) analyzed the white blood cell population and concentration of two cytokines (interleukin-1 and tumor necrosis factor (TNF) in bronchoalveolar lavage (BAL) fluid following exposure of experienced welders to fumes generated by welding galvanized mild steel. While the population of inflammatory cells increased in the BAL fluid during the first 22 hours after welding, little or no TNF or interleukin-1 was detected. The investigators concluded that they had examined the wrong cytokines and postulated that other cytokines, or a cytokine-like mechanism, may mediate the syndrome of metal fume fever.

Effects on the Ear

Thirty cases of burns to the ears inflicted by flying sparks from welding operations were discussed by two investigators (Refs. 64 and 137). Fisher and Gardiner (Ref. 64) ascribed these injuries to the lack of ear protection afforded by "visor" type helmets when working overhead or in cramped conditions with the neck flexed.

Effects on the Eye and Vision

Using a theoretical model of the human eye, Okuno (Ref. 151) concluded that infrared (IR) cataracts result from heat conduction to the lens following absorption of IR radiation by the cornea. The threshold IR irradiances for cataract formation were determined to be in the range of 163 to 178 mW/cm^2 for exposures lasting longer than 5 minutes under normal conditions. To protect against cataract formation, Okuno recommended that IR irradiance be limited to 80 mW/cm^2 for exposures over 5 minutes.

Four cases of welders with cataracts were described by Hanke and Karsten (Ref. 83). The IR irradiance received by the eyes of each of the welders was estimated from detailed occupational histories and reconstruction of their workplace routines. All four welders had routinely been exposed to doses of IR radiation in excess of the maximum safe limits recommended by Okuno (Ref. 151).

An unusual case in which a welder developed bilateral maculopathy (retinal injury) in the absence of photokeratitis, following unprotected exposure of less than two minutes' duration to a SMAW unit was described by Power et al. (Ref. 166). The investigators suggested a link between the severity of the retinal lesions in the absence of keratitis with the drug fluphenazine, which the patient had taken for 10 years for treatment of depression. They postulated that fluphenazine accumulates in the retinal pigment epithelium, where it acts as a photosensitizing agent, making the retina particularly susceptible to photochemical damage. Neki (Ref. 144) questioned the assumptions made by Power et al. and suggested that, in the absence of experimental proof, it is just as likely that the fluphenazine accumulates in the cornea where it provides protection against the action of electromagnetic radiation.

Surveys of persons appearing in hospitals with eye injuries showed that 17% of the patients treated for eye injuries in a Hospital in Denmark were welders (Ref. 9) and 11.5% of those treated for ocular foreign bodies during a six month period in a hospital in England were welders (Ref. 13). A survey of welders conducted by Ten Kate and Collins (Ref. 198) related eye injury to the use of appropriate eye protection. Forty percent of the welders reported "receiving at last one welding flash". Reports of eye symptoms (e.g., tired, sore, watery or itchy eyes) correlated well ($p<.001$) with the number of flashes received. Unprotected exposure to nearby welding was experienced by 64% of the welders.

Narda et al. (Ref. 142) found that the frequency of chronic conjunctivitis was substantially higher among welders than controls who worked in a foundry in Italy. The incidence of conjunctivitis was higher in welders who used SMAW than in those using submerged arc welding (32.4%). Norn and Franck (Ref. 149) found that spheroid degeneration (small globular, yellowish lesions on the exposed part of the conjunctiva or cornea), was more common in welders than in other workers. A significant, but much smaller increase in the incidence of pinguecula (yellow spots on the exposed conjunctival bulbi) was also noted.

Effects on the Skin

Two cases were described in which welders reacted to reflected UV radiation. The first case involved a welder who developed recurrent mild facial erythema. His condition was attributed to UV radiation reflected from a white textile hood that he wore in addition to a helmet (Ref. 92). A second welder developed facial dermatitis associated with welding. Skin testing showed an abnormal reaction to UV radiation. A shield was used while welding, so his dermatitis was ascribed to indirect exposure to UV radiation (Ref. 226).

Effects on the Nervous System

Sjogren et al. (Ref. 189) conducted a study of neuropsychiatric symptoms among 65 welders who welded primarily aluminum and 217 railroad track welders. Subjects who welded aluminum, lead, or manganese for long periods experienced significantly more neuropsychiatric symptoms than welders exposed to chromium or nickel. Depression and difficulty concentrating were associated with exposure to aluminum fume. Short memory, forgetfulness, and frequent headache were associated with welding lead-painted steel. Experiencing painful tingling sensations was associated with exposure to manganese fume.

Wechsler et al. (Ref. 218) conducted a pilot study to evaluate a range of occupational and environmental agents for potential associations with Parkinson's disease. The study compared 34 Parkinson's disease patients (average age 68.4 years) with 22 neurology clinic patients (average age 58.9 years) having diseases other than Parkinson's disease. Analysis by metal exposure in males indicated more frequent exposures to aluminum and copper. Three of the male Parkinson's disease patients and none of the controls had been employed as welders. The three welders reported exposures to aluminum but not to other metals.

Armon et al. (Ref. 7) conducted a case-control study to evaluate risk factors for amyotrophic lateral sclerosis (ALS). Men with ALS had spent significantly more time welding or soldering than controls ($p<0.01$).

Effects on the Immune System

Ulrich et al. (Ref. 207) found significant changes in humoral immunity in welders; immunoglobulin IgG increased, and IgM decreased with the duration of welding. The serum indicators of inflammation, complement and alpha-1-antitrypsin, changed significantly with the number of years welding experience.

Effects on the Musculoskeletal System

Torner et al. (Ref. 200) found that the incidence of neck and/or shoulder symptoms was more prevalent among welders than clerks from the same plant. The range of motion in external rotation of the shoulders was significantly less among the welders than the clerks and almost half (47%) the welders had atrophied shoulder muscles. Most of the welders (60%) considered their symptoms to have been caused by heavy work for a prolonged time, while only 12% attributed their musculoskeletal symptoms to a sudden incident at work.

Prolonged or awkward working postures and incorrect heavy lifts and stumbling or falling were found to be the major risk factors for accidents involving lower back injuries in welders (Ref. 96). In addition, certain stress factors, (i.e., hurry, monotony, and an accelerated working pace) were also related to lower back pain (Ref. 97). Occupationally related lower back pain was infrequently related to sudden movements.

Jarvholm et al. (Ref. 103) used electromyography and simultaneous measurement of intramuscular pressure to study the effectiveness of arm support in reducing the load on the supraspinatus muscle of the shoulder during simulated welding operations. It was determined that arm support greater than 2.2 to 3.4 pounds (force) would be needed to reduce intramuscular pressure sufficiently to lower the incidence of shoulder pain and impairment.

Marciniak and Badowski (Ref. 132) compared spinal X-rays among job applicants and experienced manual workers in a Polish automobile factory and found that the incidence of scoliosis was highest among workers in jobs that imposed the greatest spinal loading, i.e., tinsmiths, pressers, and welders.

Carpal tunnel syndrome (CTS) can result from repetitive wrist movement tasks such as welding (Ref. 160) or from use of vibrating hand-held tools (Ref. 82). Hagberg et al. (Ref. 82) found that welding was one of the four most common occupations among patients with carpal tunnel syndrome. Panio (Ref. 160) described a workplace program for the prevention of CTS that included pre-employment screening; worker training; modification of job routine to reduce unnatural angles of the wrist; modification of tools; and gloves or braces to maintain correct wrist alignment.

Effect on the Kidneys

Cadmium. Trevisan and Maso (Ref. 204) examined the reversibility of proteinuria in six cadmium-exposed welders. All of the subjects had worked in shops where brazing was performed with high-cadmium alloys and had participated in an earlier study of urine proteins before they ceased welding in 1982. Three of the subjects had no indications of low molecular weight proteinuria before they had ceased welding and their urinary protein levels remained low during the 5-year follow-up period. The remaining three welders had shown low molecular weight proteinuria, indicative of kidney tubular dysfunction, while still exposed to cadmium. During the follow-up period, beta 2-microglobinuria increased in two of these welders, while in the third there was a temporary increase in beta 2-microglobinuria which returned to normal levels after 5 years of nonwelding. These results indicate that cadmium-induced tubular dysfunction is reversible in some, but not all, persons with this condition.

Chromium. While acute kidney disease can result from massive exposure to chromium, chronic renal disease resulting from occupational or environmental exposure to chromium has not been reported. Wedeen and Qian (Ref. 219) maintained that the effects of chronic chromium exposure on the kidneys have not been adequately studied. He stressed the need for large-scale, prospective case-control epidemiologic studies to demonstrate whether or not delayed renal effects can result from low-level, long-term exposure to chromium.

Fertility

Boshnakova and Karev (Ref. 37) found that spontaneous abortions occurred significantly more frequently in the families of welders and that still births occurred significantly more frequently in families of nonwelding manual control workers.

Bonde (Ref. 32) observed an increased risk for subfertility (delayed conception) in a case-control study of 432 male welders and 240 nonwelding metal workers and electricians. In a continuation of that study, Bonde et al. (Ref. 35) examined fertility in a Danish cohort of 3702 male metalworkers. Among subjects who had ever welded, the probability of fathering a child during years when they were not welding was significantly greater than that of metalworkers who had never welded. Among persons who had ever worked as welders, the probability of having a child was slightly, but significantly, reduced during the year following a year of welding exposure. The reduction in fertility was associated with the welding of mild steel but not with SMAW or GTAW of stainless steel.

Bonde (Ref. 33) compared semen quality and serum levels of sex hormones among 35 stainless steel welders, 46 mild steel welders and 54 non-welding metalworkers. Changes in sperm quality and follicle stimulating hormone were seen in both groups of welders. Effects were most marked among mild steel welders. To determine if the changes in semen quality were reversible, semen quality was examined in 19 of the mild steel welders, 18 of the stainless steel welders and 16 of the non-welding metalworkers before and after a 3-week, welding-free vacation period (Ref. 34). No significant improvements in any of the semen parameters were observed at any of the post-vacation measurements relative to the pre-vacation values.

Effects on the Teeth

Tatintsyan and Abgaryan (Ref. 197) reported that 87% of welders have some degree of periodontal disease and gingivitis. They correlated this with a lower than normal concentration of lysozyme, an enzyme destructive to the cell wall of some bacteria, in saliva collected from the welders. These investigators developed a small filtration device to protect the mouth from exposure to welding fumes. After using the device for 2 years, lysozyme increased in saliva collected from welders.

Effects of Specific Metals

Beryllium. A typical case of chronic beryllium disease was described by Monie and Roberts (Ref. 138) in a fifty-one-year-old Scottish welder who had a long-standing cough with morning production of mucoid phlegm. His chest X-ray showed reticulo-nodular shadowing. Examination indicated reduced pulmonary function and biopsies showed mild fibrosis and epithelioid cell granulomas. Beryllium was identified in biopsied lung tissue.

Cadmium. Yates and Goldman (Ref. 225) described a case of acute cadmium poisoning which occurred following two weeks of brazing ship propellers with an oxy-acetylene torch using an alloy containing 20% cadmium. After 10 days, the patient began to experience malaise and breathlessness, developed fever and joint pain, and had reduced lung function.

Fuortes et al. (Ref. 67) described an acute fatality in a man who was using a propane torch and soldering gun to join sheet metal surfaces. He died 3 days after developing an extremely high fever, cough, and abdominal pain. Autopsy revealed pulmonary edema and congestion. Exceedingly high cadmium levels (280 ng/ml) were detected in his blood and milligram quantities of cadmium were identified on the soldering gun tip and sheet metal samples with which he had been working.

Iron. Lubianova (Ref. 126) found that the concentrations of iron and transferrin were elevated in the blood of welders. Welders without pneumoconiosis had less blood iron than welders with pneumoconiosis.

Biological Monitoring

Chromium: Biomarkers. Popp et al. (Ref. 165) examined DNA integrity in blood lymphocytes obtained from 39 stainless steel welders and 18 controls. The average sister chromatid exchange (SCE) frequency was significantly lower for welders than controls. However, alkaline filter elution indicated the presence of DNA-protein cross-links which showed that SCE analysis alone could lead to the false impression that DNA integrity remains intact in chromium-exposed workers.

Coogan et al. (Ref. 50) investigated whether chromium concentrations in lymphocytes can be used as a biomarker for long-term chromium exposure. White blood cells accumulated significantly more hexavalent chromium than did red blood cells. Chromium was undetectable in white blood cells, and present in only low levels in red blood cells, after administration of trivalent chromium to rats. The investigators concluded that the exclusive accumulation of hexavalent chromium by white blood cells supports their use as target cells in the development of biomarkers for assessing exposure.

Chromium: Biological Monitoring. Biological monitoring of low-level chromium exposures was studied by two investigative groups (Refs. 36 and 41). Bonde and Christensen (Ref. 36) examined absorption and clearance kinetics following low-level exposure to chromium in 39 welders and 18 controls. While blood and urine chromium concentrations were significantly higher in stainless steel and mild steel welders than in controls, there were no significant changes in chromium levels during the work week, and urine and blood chromium concentrations did not change during a 3-week break from welding. The investigators found these data to be consistent with a gradual buildup of chromium during long-term welding exposure.

Bukowski et al. (Ref. 41) examined factors which could confound studies of the absorption kinetics of chromium in workers who experienced low-level, intermittent exposures to soils heavily contaminated with chromium. They focused on determining nonvocational factors which could introduce errors into biological monitoring data. Males had slightly higher urinary chromium levels than did females. Beer drinking was associated with a significant increase in urinary chromium, while tobacco use or exercise caused a slight decrease in urinary chromium levels. Neither welding nor engaging in hobby activities with possible chromium exposures was associated with increased concentrations of chromium in the urine or blood.

Nickel. Angerer and Lehnert (Ref. 5) determined nickel levels in red blood cells, plasma, and urine from 103 stainless steel welders who worked with chromium-nickel alloyed steel. The authors calculated that urinary nickel levels between 30 and 50 µg/L correspond to an external exposure of 500 $\mu g/m^3$.

Aluminum. Elinder et al. (Ref. 59) measured aluminum levels in bone and urine from two workers 5 years after they had ceased routine welding of aluminum. The investigators concluded that aluminum accumulates in the skeleton and tissues following long-term inhalation exposure and that the elimination of retained aluminum is very slow, on the order of several years.

Zinc. Chughtai et al. (Ref. 49) showed that zinc concentrations were significantly higher in serum from gas and arc welders than from controls.

Incidental Exposures

Degreasing Agents. Two incidents were described in which photochemical decomposition products resulting from reaction of degreasing agents with UV radiation produced by GMAW or GTAW may have caused respiratory distress. In the first incident (Ref. 191), a welder developed respiratory distress and pulmonary edema after welding stainless steel degreased with trichloroethylene. In the second incident (Ref. 181), a welder developed severe respiratory distress and eventually died after welding metal pieces degreased with 1,1,1-trichloroethane for 3 days. Phosgene was not detected during a reconstruction of this incident at the worksite.

Coated or Contaminated Surfaces. Two cases were reported in which welders developed deficits in pulmonary function presumably from exposure to materials generated by burning of paint or other metal surface contaminants (Refs. 119 and 185). In a third case, diffuse, interstitial pneumonitis was shown to be related to long-term exposure to cutting oils (Ref. 162).

Allergens. Two welders were described who developed allergic responses to chemicals incidental to the welding process. The first welder developed bronchial asthma while welding metal pieces contaminated with chloramine-T (Ref. 28). The second welder developed an urticarial skin reaction associated with high fever and facial edema while welding nonstainless steel profiles filled with polyurethane (Ref. 107).

Investigations in Animals and Cell Cultures

Fertility

Ernst (Ref. 63) found that hexavalent chromium, administered to rats by intraperitoneal injection, causes a reduction in testicular weight and a dose-dependent increase in the number of atrophic seminiferous tubules. At the highest dose tested (4 mg/kg body weight), almost all of the seminiferous tubules were completely degenerated, and there was a marked reduction in the epididymal sperm count. Trivalent chromium did not cause these effects.

Fibrosis

Yurui and Yu (Ref. 228) demonstrated that the proportions of collagen Types I and III change during the fibrotic process stimulated by quartz but not by welding fumes. The authors concluded that the ratio of Type I to Type III collagen can be used for evaluation of the fibrogenicity of respirable dusts. Hicks and Olufsen (Ref. 89) demonstrated that myofibroblasts proliferate in fibrotic processes in lungs exposed by intratracheal instillation to crystalline silica or to fumes generated by GTAW of mild steel.

In Vitro Tests

In continuing studies of the effects of hyperbaric pressure on physiological functions, Jakobsen et al.(Ref. 101) found that increasing pressure may increase the ozone toxicity to alveolar macrophages. Using the chemiluminescence assay, Saburova et al. (Ref. 177) found that welding fumes did not elicit the formation of hypochlorous acid (HOCl) by isolated PMNs. The authors concluded that HOCl does not play a role in the pathogenic processes associated with inhaled welding fumes.

Adamis et al. (Ref. 1) tested fumes collected from GTAW of an Al-Mg alloy and dusts collected from other operations in an aluminum plant in three *in vitro* assays (erythrocyte hemolysis, interference with macrophage metabolism and lysis of macrophages). While none of the three samples was classified as hazardous, the welding fume particulates were more toxic than the other dust samples.

Animal Studies

Naslund et al. (Ref. 143) examined pulmonary effects of fumes generated by SMAW of black iron in sheep. Acute exposure to welding fumes significantly increased mean pulmonary arterial pressure and the number of leukocytes. Hematocrit values, arterial oxygen tension, and pO_2 were reduced. Chronic pulmonary exposure to the welding fumes caused fibrosing pneumonitis and slight emphysema.

Pokrovskaia and Cherednichenko (Ref. 163) examined the effects of fumes from five different welding electrodes on the cardiovascular system and respiratory tract in rats. After 1 month, there was atelectasis, swelling of the bronchial epithelium, and thickening of alveolar walls. Damaged muscle fibers were seen in the heart. At three months, there were still substantial effects in the lung and cardiovascular system. By 6 months, much of the tissue damage had resolved. Fibrosis was not observed at any time.

Geleskul et al. conducted a series of studies in which the toxicity of fumes from three different electrodes was measured by lipid peroxidation in the liver and lung (Refs. 71-73). Fume samples were administered to rats by intratracheal instillation, and malondialdehyde was determined in lung tissue or liver mitochondria. Fumes from all three electrodes stimulated the formation of peroxides. Peroxidation was greatest at 1 day after treatment in lung tissue and at 7 days after treatment in liver tissue. In a related report by Geleskul et al. (Ref. 74), the tendency for welding fumes to cause lipid oxidation was measured in liver mitochondria by determining the effects on the glutathione/glutathione reductase antioxidant system.

Velichkovski et al. (Ref. 214) compared the toxicity of fumes from four electrodes in three different assays (chemiluminescence, hemolysis of red blood cells, peroxidation of lipids in the lung). It was concluded that there is a strong correlation between the toxic activity of the welding fumes *in vitro* and in tests performed *in vivo*. Using the lipid peroxide techniques described by Geleskul et al., (Ref. 70), Kuchuk et al. (Ref. 117) measured lipid peroxidation in liver tissue and chemiluminescence in white blood cells isolated from rats treated by intratracheal instillation with fumes from 6 different electrodes.

Conclusions

During this report period, important areas of research on the health effects of welding focused on the effects of long-term exposure to low levels of chromium, and the potential effect of welding on fertility. In addition to these studies, Sjogren et al. (Ref. 189) focused attention on potential neurologic effects associated with long-term exposure to aluminum. It is expected that these areas will continue to receive attention in the future. Investigations of the effects of low-level exposures, and also those which are attempting to measure small effects of exposure, are particularly sensitive to errors introduced by nonvocational exposures and, thus, results must be viewed with caution. This is especially true of studies such as those conducted by Bonde on fertility in welders. Carefully planned laboratory studies in animals and epidemiologic studies in humans are necessary to resolve questions raised by researchers in these areas.

Effects of Welding on Health IX

Section One
The Exposure

1. Introduction

Welding fumes and gases originate from vaporization of the welding rod or wire, decomposition and vaporization of the flux materials, spatter and fumes from the arc region and weld pool, and evaporation from the molten weld metal. All of the chemical elements found in the welding electrode, flux, workpiece, and shielding gases are present in the welding emissions. But, because of differences in volatility, their proportions in the fume may not parallel their proportions in the welding consumables and workpiece. Metals with low melting points, such as manganese, copper, and lead, are enriched in the fume, compared to more refractive elements such as iron, chromium, and nickel (Ref. 100).

The fume generation rate (FGR), or the total quantity of fume emitted per unit time (e.g., gram/min), is lowest with gas tungsten arc welding (GTAW), followed by gas metal arc welding (GMAW), and highest with shielded metal arc welding (SMAW) and flux cored arc welding (FCAW). The electrode is the source of a much greater proportion of the total emissions than is the workpiece. Solid electrodes have the lowest FGR. Flux cored wires have a higher FGR than do comparable covered electrodes, but flux cored wires also deposit more metal in a given period, so that the mass of fume generated per kg of weld (relative fume formation rate, RFFR) is comparable (Ref. 14). Helmet design, the welder's posture and position relative to the plume, and ventilation affect the extent of a worker's exposure to welding emissions (Ref. 19). The use of robotics has the advantage of removing the operator from the immediate vicinity of the plume, reducing exposure to the most intense fumes and radiation. However, because robotic welders are capable of continuous operation for long periods of time, more fumes are can be generated than with manual welding, and requirements for exhaust ventilation may be increased (Refs. 12 and 102).

2. Fumes

Wisniewski (Ref. 223) analyzed cinematic films of metal droplet transfer in the welding arc during GMAW using carbon dioxide (CO_2) or mixtures of Ar+O_2 or Ar+CO_2 as the shielding gas. At low welding currents, molten metal forms into droplets on the tip of the filler wire; when the droplet diameter is larger than that of the wire, the droplets separate and pass into the pool of molten metal. Vaporization from the droplet as it separates from the wire can have an "explosive character", originating in the "neck" of the drop, promoting the formation of fumes. Processes which reduce the final growth phase of the droplet, reduce fume formation. As the welding current is increased to the spray mode, particles with diameters smaller than the filler wire are transported axially to the molten pool. In this phase, the droplets tend to stay intact until they hit the workpiece and fume formation is confined to the region of the arc, which reduces the quantity of fume. When the shielding gas is moving at low velocities, vaporization is limited by diffusion of the metal vapor. At higher shielding gas velocities, vaporization into the surrounding air is enhanced by convection.

Hewitt and Hirst (Ref. 87) developed a model to predict the composition of welding fumes generated by SMAW and FCAW. Two mechanisms of transfer of metal to the fume were considered: fractionated transfer, in which the metals evaporate at different rates dependent on their partial vapor pressures, and direct transfer, which results from surface depletion and spatter, is independent of melting point, and in which the metals are present in the aerosol in the same proportions as in the original materials. Transfer coefficients for use with the model were developed from experiments in which different base plates were welded with flux cored mild steel wires of varying composition. The fume composition predicted on the basis of these transfer coefficients closely agreed with compositions determined experimentally. In these experiments, 45% of the fume was derived from the flux, and 39% was derived from the wire sheath, even though the flux represented only 18% of the total weight of the wire. Fractionated transfer accounted for 78% of the fume. This is consistent with the high contribution of the flux which, being in the core of the wire, is not accessible for direct transfer.

Hilton and Plumridge (Ref. 91) conducted an extensive series of tests of the effects of welding current and various shielding gases on the quantity of fumes generated by GMAW of various base metals. When welding mild or stainless steel with solid electrodes, the FGR rose steadily as the current was increased until an unstable transition mode was encountered at about 170 A (see Figure 1A). With argon shielding gases, the FGR decreased or leveled out with increasing current above 170 A, as a spray mode of transfer was achieved. When mild steel was welded with a CO_2 shielding gas, the spray mode was never achieved, and the FGR continued to increase with increasing current. Welding stainless steel with a rutile flux-cored wire generated more fumes, but less chromium, than did welding with a solid wire. Helium-based shielding gases produced more fumes than did argon-based shielding gases during GMAW of stainless steel, copper-base materials, or aluminum alloys (Figure 1B). At currents above 150 A, more fumes were generated by GMAW of an aluminum alloy containing 5% magnesium than by GMAW of an aluminum alloy containing 5% silicon (Figure 1C). This alloy effect was much more pronounced than was the effect of the helium shielding gas. In general, fume levels generated by GTAW using argon-based shielding gases were much lower than those produced by GMAW.

Oleinichenko et al. (Ref. 153) measured the effect of welding current and voltage on the composition of welding aerosols using flux-cored strips. At 32 V, the rate of melting increased by 39% as the current increased from 600 to 800 A. The RFFR, measured in g/kg of electrode, increased by 34% as the current increased from 600 to 800 A, and manganese increased by 7.5%, vanadium by 120%, and hexavalent chromium [Cr(VI)] by 10%. At a constant current of 800 A, the rate of melting increased only another 5% as the voltage increased from 32 to 36 V, but the RFFR increased by an additional 37%.

Olah and Pospisilova (Ref. 152) characterized fumes generated by welding high-alloy steel with various welding techniques. SMAW with tubular wires produced the highest FGR. Solid electrodes with a high chromium and cobalt content had a lower FGR, but the rate of fume generation per gram of weld (RFFR) was greater. GMAW using wires with a high chromium and nickel content produced less fumes, but the chromium content of the fume was so high that chromium emissions were almost equal to those from SMAW. GTAW using wire high in chromium and nickel generated about one-tenth the quantity of fumes produced by SMAW. Although the fumes contained up to 23% chromium, GTAW still produced the lowest quantity of total chromium of all the processes studied.

Medack and Heinze (Ref. 135) measured and characterized the emissions from GMAW of steel coated with zinc, tin, and aluminum. Four to six times more fumes were generated by welding metal sheets coated with zinc and tin than by welding aluminum-coated and uncoated steel. When the emissions associated with welding these coated steels were compared with allowable workplace exposure limits, zinc was the limiting factor for zinc-coated steel, for tin-coated steel it was lead, and for aluminum-coated or uncoated steel it was manganese which originated from the electrode.

Mori et al. (Ref. 140) measured the chromium and nickel generated by SMAW with three Japanese flux-coated electrodes containing 9 to 13% chromium and 39 to 68% nickel and by submerged metal arc welding with a nickel alloy wire. The base metal was mild steel containing no chromium or nickel. Fumes were collected at 12 sampling points arranged in a three-dimensional matrix at three heights directly above the arc and, at the same three heights, displaced 50 cm from the front, to the rear, or to one side of the arc. SMAW produced more fume than did submerged arc welding. Using an electrode with 12.2% chromium and 68.1% nickel, the fume concentration was 254 mg/m^3 and the chromium content was 5.3% at a height of 50 cm directly above the weld. At 150 cm and 250 cm directly above the weld, the fume concentrations were 68 and 65 mg/m^3, respectively, and the chromium concentrations decreased to 4.3%. Fume concentrations were dramatically lower in samples collected at the side and in front of the arc, and chromium was only detected in one of these samples. Directly above the arc, nickel concentrations decreased from 0.54% at 50 cm to 0.25% at 150 and 250 cm. Submerged arc welding of the nickel wire produced fume concentrations of 118, 13, and 6.6 mg/m^3 at 50, 150, and 250 cm directly above the weld, respectively. Notably, the percentage of nickel in the fume from the submerged arc welding process increased with sampling height above the weld, which was attributed to the low density of nickel oxide compared with iron oxide.

Eichhorn and Nies (Ref. 58) evaluated a variant of the narrow-gap submerged arc welding process with two wire electrodes. The system used smaller and more easily manipulated welding heads and was purported to be more efficient and flexible than conventional single wire electrode techniques. Large quantities of fumes were generated in tests with a barium-containing welding powder, used to increase the shrinkage of the slag during cooling. While this is unlike conventional submerged-arc welding which is characterized by extremely low fume emissions, the fumes were still considerably less voluminous than those formed during FCAW with barium-

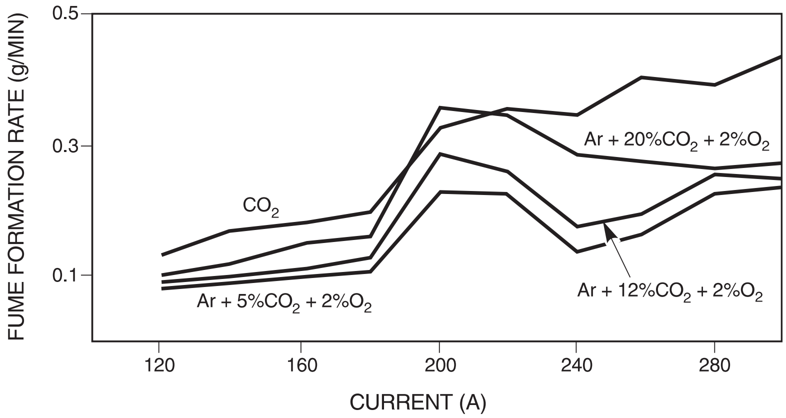

Figure 1A—Fume Generation Rate During GMAW of Mild Steel Using Solid Mild Steel Wire Showing the Effects of Increasing Concentration of CO_2 in the Shield Gas with Increasing Current. Hilton and Plumridge, Ref. 91

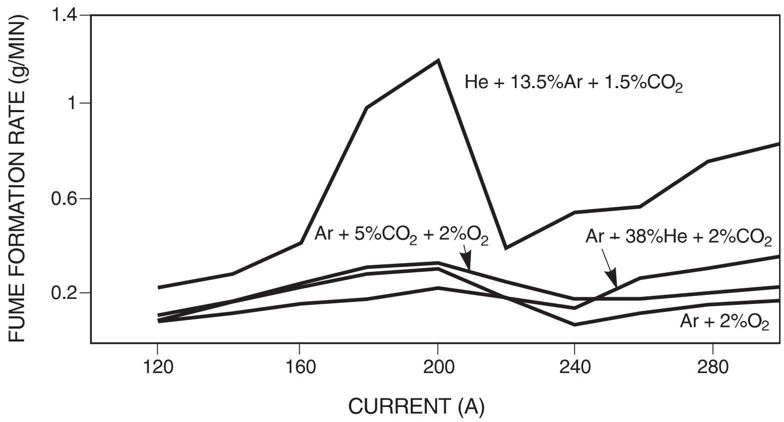

Figure 1B—Fume Generation Rate During GMAW of Stainless Steel Using Solid Stainless Steel Wire Showing the Effects of Helium in the Shield Gas with Increasing Current. Hilton and Plumridge, Ref. 91

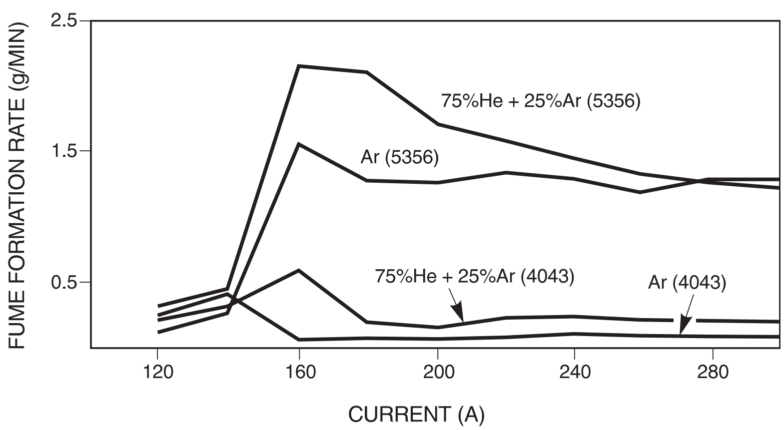

Figure 1C—FGR for GMAW of Aluminum Alloys Containing Either 5% Magnesium (Alloy No. 5636) or 5% Silicon (Alloy No. 4043) Showing Effect of Magnesium in the Metal and Helium in the Shield Gas with Increasing Current. Hilton and Plumridge, Ref. 91

containing flux cored electrodes. In addition, barium accounted for 12% of the fume with the narrow-gap submerged arc process, compared with up to 32% of the fume from flux cored welding. The investigators concluded that local ventilation would be capable of preventing barium concentrations from exceeding the workplace limit (0.5 mg/m^3).

2.1 Analytical Techniques. Ukkonen et al. (Ref. 206) described a method for determining the mass median diameter of an aerosol by combining data from two real-time aerosol monitors (a photometer and an electrical aerosol detector). The method worked well for particles with densities close to unity (tobacco smoke and dioctyl phthalate). However, because of their high density, estimated by Ukkonen et al. to be 3 g/cm^3, the method did not accurately determine the diameters of welding fume particulates.

Battistoni et al. (Ref. 17) used an aerosol photometer to measure particle concentrations at points 0.3 and 1.8 m above a Migtrain (TM, Kobe Steel Ltd.) automatic welding system (GMAW) using a mixture of 80% Ar and 20% CO_2. From the two measurements, an overall emission rate of 9.6 mg/min was calculated using a two-point eddy diffusion model.

Particles in welding fumes are formed by condensation of vapors of metal oxides to form condensation nuclei which further interact with each other and with uncondensed vapors to form larger particles. During this process of particle-building, the concentrations of the various components of the particle may not be homogeneously deposited throughout the depth of the particle, and certain elements may be enriched on the surface while others may be present in higher concentrations inside the particle. Goschnick et al. (Ref. 80) used secondary neutral mass spectrometry (SNMS) to analyze the composition of particles generated by SMAW with a stainless steel electrode. Chromium in the fume particles was enriched by a factor of three relative to iron, based on the original composition of the electrode. Removal of successive layers by argon sputtering revealed no variations in the chemical composition between external and internal layers of the particles. This contradicts earlier work by Grekula et al. (Ref. 81) and Malmqvist et al. (Ref. 129) who, using scanning electron microscopy and energy dispersive X-ray analysis, showed differences in the chemical content of the surface and core of particles generated by SMAW of stainless steel.

Bauer et al. (Ref. 18) compared two methods for determining Cr(VI) in fumes from GMAW and SMAW of stainless steel. With the first method, area and breathing zone samples were collected on polytetrafluoroethylene (PTFE) filters. The PTFE filters were eluted with alkaline buffer solution and Cr(III) and Cr(VI) were captured by anion exchange resins. In the second method, fume samples were collected on glass fiber filters. The filters were placed in an absorption medium in a PTFE flask, rinsed with distilled water, filtered through a 0.2 µm cellulose acetate filter, and acidified with nitric acid and ammonium nitrate. For both methods, Cr(VI) was determined by AAS. The results of the two methods were comparable for both personal and area samples. The samples could be preserved in alkaline carbonate for 3 days without affecting the Cr(VI) measurement.

2.2 Analysis of Metals in Biological Tissues. Identification of metals in biopsied or autopsied tissues is sometimes useful in discerning the cause of disease. Seemann et al. (Ref. 180) investigated whether trace elements can be reliably determined in lung tissue specimens that have been fixed and stored in formalin, because occasionally only fixed tissues are available for examination. In this work, the chromium and nickel contents of eight postmortem lung specimens were determined in the lungs from four men who had died of lung cancer between 1988 and 1989. One of these men had been employed as a plumber and did soldering and welding for 40 years. Two of the other men had been coal miners, and the occupation of the third man was not specified. Chromium and nickel concentrations were determined by flameless atomic absorption spectrometry (AAS) after lyophilization, wet ashing under pressure, chelating, and extraction. The concentration of chromium and nickel was markedly higher in the lung tissue from the welder than from the other three men. The investigators concluded that their method provides a reliable means of determining trace metals in fixed lung tissue.

3. Workplace Exposure Limits

Balchin (Ref. 12) reviewed the British health and safety regulations as they apply to welders, noting that standardization of these regulations within the European Community (EC) was being anticipated by adopting, in part or in whole, the EC's European Norms as British Standards. Sutton (Ref. 194) evaluated the intrinsic hazards of substances used, or arising from the welding of stainless steel with respect to the British Control of Substances Hazardous to Health Regulations of 1989. He observed that in fumes from SMAW of stainless steel, hexavalent chromium [Cr(VI)] is usually the hazardous component that determines the requirements for air cleaning or personal protection. The Cr(VI) content of the fumes produced by GMAW and GTAW is so much lower than the Cr(VI) content of fumes from SMAW that the standard for total chromium of 0.5 mg/m^3 can usually be applied.

Dryson and Rogers (Ref. 55) conducted a survey of airborne contaminants in the breathing zone of 16 welders performing SMAW, GTAW, GMAW, and plasma cutting in seven New Zealand industrial plants. Samples were collected inside the welding helmets for 2 to 4 hours, during that part of the workshift devoted primarily to welding. Urine samples were taken at the end of the shift on the same day as the breathing zone samples. Total dust levels were higher for SMAW, plasma cutting, and GMAW than for GTAW. Levels of ozone, fluoride, and zinc were not greater than 20% of the New Zealand workplace exposure standards in any of the samples collected. Of the 16 welders in the study, six were exposed to excessive levels of at least one pollutant. Allowable limits for total fume, nitrogen dioxide, and chromium were occasionally exceeded. Analyses of urine did not show excessive absorption of nickel or chromium.

Van der Wal (Ref. 213) analyzed fumes and gases collected in area samples and in breathing zone samples from welders working at 18 different plants and locations in Holland. All of the work was performed in large rooms without local exhaust ventilation. Data from previous studies (Ref. 211 and 212) were included in the analyses. Figure 2 shows the distribution of fume concentrations in the breathing zone generated by different welding methods. GTAW was the only welding process for which there were no measurements of breathing zone fume concentrations exceeding the Dutch occupational health standard (TLV) of 5 mg/m^3. SMAW and GMAW of stainless steel produced Cr(VI) levels above the Dutch TLV (0.05 mg/m^3) as did polishing of stainless steel, but plasma welding or cutting of stainless steel did not produce excessive levels of total chromium or Cr(VI). Carbon monoxide (CO) levels were below the Dutch TLV of 50 ppm, except for metal spraying operations, where they ranged from 40-160 ppm. No measurements of NO_2 exceeded the Dutch TLV of 5 ppm. Ozone concentrations did exceed the Dutch TLV of 0.1 ppm for GMAW of stainless steel and aluminum, FCAW of mild steel, and plasma cutting of Inconel alloy.

Withers et al. (Ref. 224) used Particle-Induced X-ray Emission (PIXE) to analyze elements in fumes collected inside the helmets of welders during spot welding of zinc-plated steel sheets. Relative concentrations of chromium, manganese, iron, copper, zinc, and nickel were determined. Iron was the predominant metal found in all but one of the samples. The proportion of zinc, the second most common metal, varied from 7% to 48.5%. While repeated analyses of a single sample showed good reproducibility, there was a large variability in the relative concentrations of elements among different samples. Because of this, Withers et al. (Ref. 224) concluded that no single element can be used as an indicator for the concentrations of other elements in a sample and a monitoring program based on the analysis of one reference element may be ineffective.

Paul (Ref. 161) measured lead exposures during welding and cutting operations in 130 automobile body repair shops in Dresden, Germany. The welding fume concentrations in the workplace air exceeded the German Democratic Republic (GDR) standard of 5 mg/m^3 in more than 50% of the measurements taken during welding operations and 90% of those taken during cutting operations. During welding of car bodies, lead levels were rarely in excess of the GDR standard of 50 $\mu g/m^3$, but fume concentrations from cutting operations exceeded the standard more than 50% of the time. The high environmental lead levels in these body repair shops were attributed to lead used in car finishes and lead in street dust deposits on the car bodies.

Gorban et al. (Ref. 78) investigated emissions from a series of Russian electrodes used in welding of iron and stainless steel without preheating. The emissions of NO_2, CO, and hydrogen fluoride (HF) from these electrodes were insubstantial. They measured the FGR and the RFFR for iron, manganese, nickel, copper, silicon, and soluble and insoluble fluoride, but not for chromium, and calculated the volume of air necessary to dilute the emissions of the most critical component from each electrode to a concentration below the workplace standards in the Soviet Union. They concluded that the workplace standards could be achieved using these electrodes in a well-ventilated workplace.

Zaks (Ref. 229) evaluated published data on the emissions from several different covered electrodes in terms of allowable workplace limits. Among the coatings evaluated, total fume emissions were generally greatest with acid coatings, least with rutile coatings, and intermediate with ilmenite coatings. Manganese, HF, CO, and nitrogen pentoxide were measured, and the volume of air that would be necessary to dilute all of the measured emissions to below the Soviet Union workplace limits was determined. Manganese was the governing emission in the case of acid ilmenite, rutile, and cellulose coatings, but fluoride was the critical emission for some of the electrodes with basic coatings. For stainless steel electrodes, the Cr(VI) emission rate varied from about 0.15 to 1.0 grams chromate per kg electrode, with the median content of 0.4 g Cr(VI)/kg electrode (Ref. 230). Zaks concluded that there is a large variation in emission characteristics reported by different investigators, even for the same types of electrodes.

4. Ozone

Ozone is generated from atmospheric oxygen by the action of ultraviolet (UV) radiation. GMAW and GTAW of aluminum generate the highest ozone levels, but GTAW and GMAW of stainless steel can also generate

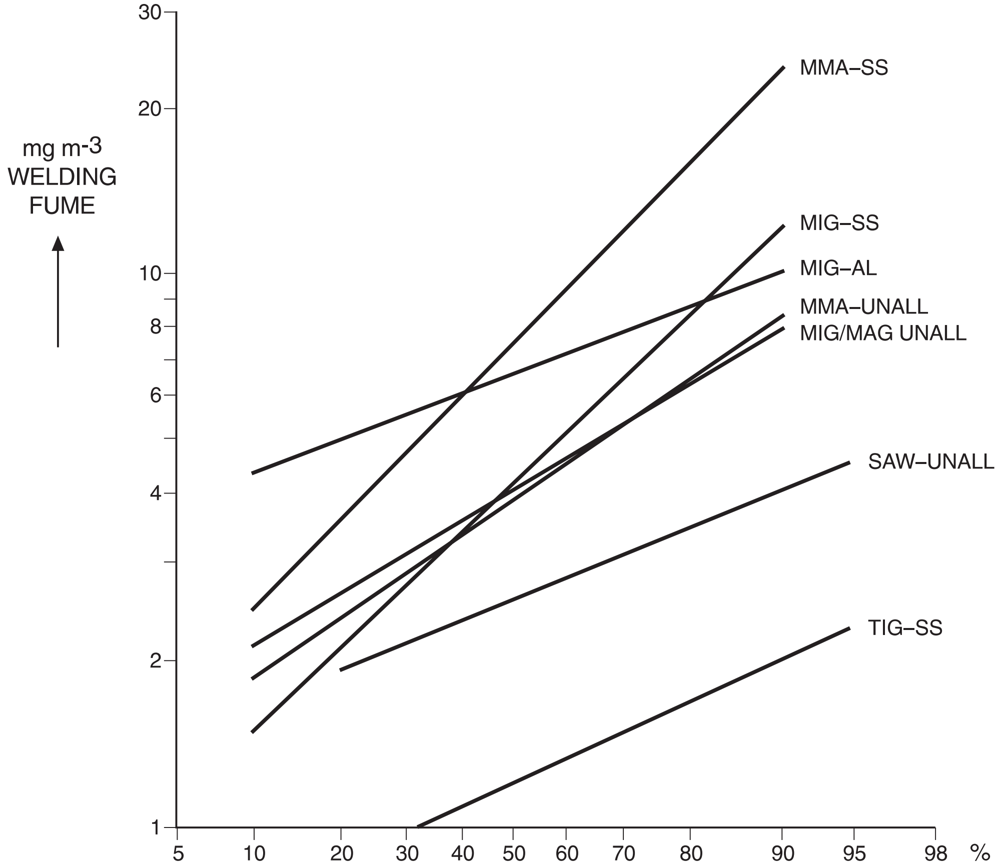

Figure 2—Cumulative Frequency Distribution of Welding Fume Concentrations in the Breathing Zone of Welders During Welding without the Use of Local Exhaust Ventilation. (MMA-SS = SMAW of Stainless Steel; MIG-SS = GMAW of Stainless Steel; MIG-Al = GMAW of Aluminum; MMA-unall = SMAW of Unalloyed Steel; MIG/MAG unall = GMAW of Unalloyed Steel; SAW-unall = Submerged Arc Welding of Unalloyed Steel; TIG-SS = GTAW of Stainless Steel). Van der Wal, Ref. 213

substantial amounts of ozone, particularly with argon shielding. Ozone is highly reactive and is rapidly consumed by reaction with other components of the welding fume. Thus, welding processes that generate large quantities of fumes (SMAW and FCAW) are not generally associated with high exposures to ozone. Conversely, a reduction in the FGR may result in increased UV radiation and, consequently, increased ozone formation (Ref. 14). The highest concentrations of ozone are normally found within 50 cm of the arc. However, because the path of UV radiation can sometimes allow it to escape absorption by the fumes, ozone may be generated at a short distance from the arc, but outside the plume of welding fumes, thereby, escaping reaction with fume components (Ref. 194).

Brehme et al. (Ref. 38) used a chemiluminescent ozone monitor to simultaneously measure up to 16 ozone concentrations in the welding plume and in the breathing zone of welders. The tests were conducted during various gas shielded welding operations in three German manufacturing plants. In all of the plants, the average concentrations of ozone in the breathing zone were well below the workplace limit of 0.1 ppm. Ozone concentrations were lowest in an automobile plant using argon-shielded GMAW, and highest in a chemical apparatus plant where GTAW was performed with a 100% argon shield. In a machinery manufacturing plant, breathing zone ozone concentrations were slightly higher when ventilation was used than when it was not, indicating that the ventilation system was improperly designed. In applications involving aluminum or aluminum/magnesium electrodes, the ozone concentrations often exceeded the 0.1 ppm workplace limit without ventilation and sometimes reached the allowable workplace limit even with the use of local ventilation.

Olsson et al. (Ref. 156) found that a shielding gas containing Ar plus 8% CO_2 is optimum for GMAW at welding currents greater than 150 A. They recommended inclusion of 0.08% nitric oxide (NO) to convert the ozone to O_2. This reaction also converts the NO to NO_2, which they state is less harmful than ozone to the welder.

5. Electromagnetic Radiation

Welders may be exposed to radiation from their own arc or from the arc of nearby welders. A common occasion of inadvertent exposure occurs when striking the arc. Since welders are often unable to see through the lens in the welding helmet, to position the electrode they must raise the face piece and then flip it down with a head motion as the arc is struck. Mistiming of this maneuver can result in exposure of the eyes to intense radiation from the arc (Ref. 198). According to Bauer (Ref. 20), protection from this type of injury is now available in welding helmets with lenses that darken on arc ignition.

Barth et al. (Ref. 15) monitored the exposure of nonwelders (bystanders) to UV generated by GMAW with a CO_2 shield. The UV exposures of nonwelders, recorded with polysulphon films, were 8 times higher than the limits recommended by the National Institute for Occupational Safety and Health (NIOSH). Clinical examinations showed that chronic damage of the external parts of the eyes occurred more than twice as frequently in bystanders than in controls. Chronic conjunctivitis and pinguecula (yellow spots on the exposed conjunctival bulbi) were the most common outer eye symptoms observed among the bystanders. These results indicate the need for the use of shields to protect persons working in the vicinity of welding job sites from UV radiation.

The use of lasers in welding applications creates another occasion for exposure to UV radiation. Injury to the eye can occur not only from directly viewing the beam, but also from exposure to reflected laser radiation. UV lasers are particularly hazardous because their beam is invisible (Ref. 95).

Lasers are classified into four hazard categories, with class IV being the most dangerous. The majority of industrial lasers used in manufacturing are Class IV and, thus, special safety features are required to prevent exposure. Class IV lasers present a radiation hazard to the skin and eyes of unprotected operators or bystanders. With infrared (IR) laser beams, visible light and UV radiation are released during laser/target interactions. In selecting eye protection, it is important to consider not only scattered laser radiation, but also noncoherent UV radiation and blue light. Heat-resistant clothes and gloves must be chosen to resist the scattered IR laser beams (Ref. 90).

Industrial laser systems package the laser inside an enclosure designed to attenuate the accessible radiation to a Class I level. Safety features include a system of interlocks which shut down the entire system should hazardous conditions develop. Other safety features of the work station include magnified viewing of the work area provided through a closed circuit television, or microscope viewing of the workpiece. Also, the use of optical fibers to deliver the laser radiation to the workpiece affords more control of the laser beam (Ref. 109).

The standard welding curtains used in conventional welding are not useful for laser welding because they cannot withstand the high energy of the laser beam. An effective laser barrier should both identify locations of laser work areas and impede transmission of laser beams outside the welding area, preventing exposure of unprotected workers. Another useful function of the barrier is to allow the detection of stray laser beams. The laser barrier curtain design described by Wilson (Ref. 220) includes a simple barrier coating that is visually marred upon exposure to stray laser beams. The location of marks on the barrier can indicate improper beam position, variation in beam intensity, or inappropriate weld technique. Any visual changes in the curtain would then indicate that unsafe welding conditions are, or were, present. Marks on the barrier could also be used to train workers in proper laser application techniques.

Hazards associated with the use of laser technology include not only the potential for exposure to radiation, but also electrical hazards, hazardous chemicals required for laser operation, and toxic gases and particles generated during the use of the laser. As with conventional welding, emissions must be properly removed to eliminate exposure to toxic chemicals (Ref. 109).

Engel et al. (Ref. 60) described research conducted in the Federal Republic of Germany using a pilot installation developed to study the emissions from cutting and welding with lasers. Studies of emissions from cutting steel with CO_2 lasers showed that more fumes are released when cutting stainless steel than nonalloyed steel. The particle size range was very narrow in emissions from all steels; 87% of the particles from galvanized steel, 85% of the particles from stainless steel, and 76% of the particles emitted from nonalloyed steel were between 0.021 µm and 0.18 µm in diameter. Elemental analyses indicated that the composition of the particles is similar to that of the parent metal. With galvanized steel, the proportion of iron increased, and that of zinc decreased with the thickness of the metal being cut.

Electron microscopic analyses showed that the particles exist as individual spheres and as agglomerates of spherical particles.

Hietanen and von Nandelstadh (Ref. 90) evaluated hazards associated with optical radiation generated during the operation of lasers in metal industry applications. The intensities of both the laser beam and scattered laser radiation were determined. During normal work shifts, the diffuse reflection of the laser beam was small. The maximum irradiance measured was about 100 W/m^2, compared with the maximum permissible exposure of 1000 W/m^2. Maximum permissible exposure times for unprotected eyes during normal operations of the tested laser were calculated to be 95 seconds for CO_2 welding of stainless steel and 124 seconds for carbon steel.

6. Electromagnetic Fields

Electromagnetic fields (EMFs) are produced by electric arc welding power sources. Zyubanova et al. (Ref. 232) calculated the intensity of the magnetic field created by current flowing through electric arc welding equipment. They showed that exposure to magnetic fields could be minimized by increasing the distance between the welder and the electric wires and by keeping the distance between the power cables to a minimum (e.g., by using coaxial cable).

7. Incidental Exposures

7.1 Production Coatings. A laboratory study of thermal degradation products of paints used on steel in the Finnish ship building industry was conducted by Henriks-Eckerman et al. (Ref. 84) to develop a simple and representative sampling procedure for the workplace. Pollutants generated by heating painted steel plates to about 350°C were collected with an array of sampling devices (adsorption tubes, bubbler absorbers, and filters) and analyzed by high-pressure liquid chromatography and gas chromatography/mass spectroscopy (GC/MS).

Low molecular weight aldehydes and acids were emitted from all paints. The most abundant degradation products usually originated from the paint binders and included phenol and bisphenol-A from epoxy paints, aliphatic organic acids and phthalic anhydride from alkyd paints, and butyraldehyde and butyric acid from polyvinylbutyral paint. Toluene, xylene, ethylbenzene, propanol, butanol, methyl isobutylketone and cyclohexanone were detected and were thought to arise from the paint solvents. Hydrogen chloride (HCl) was emitted from chlorinated rubber. Low molecular weight aldehydes, acids, and solvents were also detected. Ethanol was a typical emission from ethyl silicate shop primers which emitted the least irritating degradation products. On the basis of this work, the investigators recommended a sampling procedure for on-site studies which included a chemosorbent tube for aldehydes and a tube of adsorbent resin preceded by a glass fiber filter for particulates and condensable organic chemicals.

Using this sampling procedure in a Finnish shipyard, Engstrom et al. (Ref. 61) studied the exposure of metal workers to paint degradation products generated by welding, flame cutting, and straightening painted steels. With the exception of the higher molecular weight aliphatic acids, which may have been more completely degraded in the workplace, the same degradation products were identified in the field as in the laboratory. Straightening processes produced the lowest quantity of total fumes but generated organic pollutants in amounts equal to those produced by the other processes. This indicated a special need to monitor organic compounds and to not rely on measurements of total fume when evaluating risks associated with the straightening process.

Concentrations of individual compounds were usually below allowable limits. Even so, there were some complaints of irritation, suggesting that effects were additive. The investigators suggested changes in the design process to reduce the risk of exposure to irritants and organic compounds generated from paints on surfaces to be welded. The use of ethyl silicate shop primers would substantially reduce exposures to irritating degradation products. Areas to be welded should be left bare whenever possible by procedures such as masking with tape before painting or by removal of paint before welding. In some special types of work, such as flame cutting, which generate large quantities of organic pollutants, special respiratory protection (e.g., air supplied helmets or respirators) may be necessary.

A health hazard evaluation was undertaken by NIOSH in response to a request by an employee who became light-headed and nauseated on three occasions during the computerized, semi-automated plasma arc cutting of polyvinyl chloride (PVC)-coated galvanized steel sheets (Ref. 6). The investigators demonstrated that, while little or no fume was visible during the cutting of the uncoated sheets, a large, spreading plume of smoke was generated by cutting the PVC-coated steel sheets.

7.2 Radiation Exposure. Onodera (Ref. 157) characterized the aerosols generated during the decommissioning of a nuclear power plant in Japan. Cutting ^{60}Co-contaminated stainless steel pipe with a plasma torch generated fumes at a much greater rate than cutting with a band saw or reciprocating saw. However, 30 times more radioactivity was released per cut with the reciprocating saw than with the plasma torch. Cutting the reactor's internal stainless steel components under water markedly reduced emissions of fumes and airborne radioactivity. Radioactive emissions were 100 to 1000-fold higher when cutting the stainless steel clad reactor shell with an oxyacetylene torch in air than when cutting with a plasma arc underwater.

Carmichael and Haynes (Ref. 46) described the emissions of tritium (a radioisotope of hydrogen) encountered during the repair of distillation columns used for extracting tritium from tritiated water at a Canadian nuclear power plant. Tritium and tritium oxide were emitted while cutting the columns with a tube cutter, welding the tube ends, or heating the cut area with a propane torch. Grinding after welding did not introduce further radioactive contamination but may have enhanced its spread. The use of rubber gloves and plastic suits, limiting work periods to one hour, and isolation of the tritium-emitting work in plastic tents with local area ventilation prevented measurable tritium uptake by the workers, whose exposures were monitored by measuring levels of radioactivity in urine.

8. Hygiene and Work Practices

8.1 Ventilation and Air Cleaning Equipment. Workplace exposure to welding fumes may be reduced by natural or forced air dilution, by exhaust hoods at fixed locations, by fixed or portable local exhaust systems, or by exhaust systems mounted on the welding gun (Ref. 21). Capture of welding fumes as close to the source as possible is most desirable. Vidmar (Ref. 216) surveyed available equipment and provided guidelines for its design and selection. Fixed hoods may be used for repetitive welding in the same location, but movable hoods or portable fume/dust collectors, either connected to a central air cleaning system or equipped with intrinsic air filters, are necessary when welding is performed in multiple locations or with varying welding gun positions. Centralized collection systems, used when source capture is not possible, are less efficient and require cleaning of much larger volumes of air.

Three types of particle removal devices are used with welding fume extraction systems to prevent exhaust air laden with welding fumes from being released into the atmosphere. Electrostatic precipitators can capture very fine particulates. Bag filters and cartridge filters can handle a wide variety of pollutants. While bag filters have been the predominant fume collection method, they are being replaced by cartridge filter systems, which can capture large amounts of particulates in a small area. Removal of odors or organic vapors is usually accomplished with these systems by passing the filtered exhaust air through a bed of granular activated carbon (Ref. 216).

Tum Suden et al. (Ref. 205) used computer simulations to estimate the capture efficiencies of eight different welding hood configurations for SMAW. Their results correlated well with breathing zone particle concentrations determined experimentally using a welding fume simulator developed by the American Welding Society (Ref. 4). The flow rate through the hood, the hood aspect ratio, and the welder's position relative to the hood significantly affected the breathing zone fume concentration.

Jakubcik (Ref. 102) described ventilation and air filtration schemes in a large welding shop in Czechoslovakia. Improved ventilation when tack-welding long pressed pieces was achieved by enclosing the piece in a ventilated manifold made of removable sections which can be opened at the section where welding takes place. Jakubcik's study also demonstrated that a large mobile, multi-stage filter could maintain welding-generated pollutants in workplace air below regulatory limits even when conducting GMAW with a robotic welder using a 2.5-mm wire with an FGR of 19 mg/sec.

Van der Veen and Regensburg (Ref. 210) designed an "ergonomic welding table" designed to reduce the static loads on the arm muscles and alleviate uncomfortable working positions while at the same time reducing some of the hazards associated with welding. Three sides of the table slope backwards to guide thermal flow away from the welder. Built-in ventilation removes 90 to 95% of the welding fumes and gases. The interior surfaces are coated with UV-absorbing materials to block exposure to indirect radiation, and the height of the table was made adjustable to allow the welder to assume the most comfortable position relative to the workpiece.

Cornu and Muller (Ref. 51) used helium as a tracer gas to measure effectiveness of gun-mounted fume exhaust devices. They concluded that the position of the exhaust vents in relation to the fume being generated is very important in determining collection efficiency. Several Russian studies described fume collection and air cleaning devices. Romanenko (Refs. 172 and 173) and Gorban (Ref. 79) evaluated small-scale fume collectors equipped with filtration devices. Butenko (Ref. 45) evaluated a small-scale filtration device, and Efimov (Ref. 57) evaluated a large hood to be used with automatic welders.

8.2 Protective Gear. Steinegger and Walti (Ref. 193) evaluated two systems which used activated carbon filters to remove ozone from the breathing zone during GMAW. The first was a half-face mask, placed over the nose and mouth; the other used a pump to provide filtered air inside the welding helmet. The efficacy of these devices was assessed during GTAW of AlMgSi1. Both systems reduced the ozone concentration in the breathing zone at least tenfold, and it was concluded that either mask could be used to conform with allowable workplace limits for ozone.

Alekseeva et al. (Ref. 3) tested seven sets of masks designed for protection from welding aerosols and intense visible light. Particles smaller than 0.4 µm penetrated the filters more readily than particles between 0.5 and 0.9 µm in diameter. The resistance to breathing was judged to be negligible as there was only a slight difference in pressure inside and outside the mask. The optical filters were judged to be inadequate by welders who wore them while conducting SMAW, GTAW, and GMAW. Manz (Ref. 131) noted that welding helmets with filter plates provide protection against radiation, sparks, and spatter, but are not intended to protect against larger flying fragments generated by chipping, grinding, and polishing. Goggles or glasses with side shields are generally necessary to provide eye protection during these operations.

Jung (Ref. 105) examined the protection and durability offered by heat- and flame-proof clothing. They found that some materials lost their resistance to ignition after 10 to 20 laundering cycles. This was true even for clothing treated with a commercial product guaranteed to provide permanent protection against flames. The heat protection provided by thirty materials was tested and ten were found to be superior to asbestos.

8.3 Accidents. Reports on selected fatal accidents that occurred at construction sites between 1979 and 1982 were analyzed by Trent and Wyant (Ref. 203). Of the 20 reports of fatalities that involved welders, ten were due to falls or to being struck by falling objects. Seven were due to environmental hazards such as electric lines, combustibles, explosive substances and atmospheres, and pressurized lines and vessels; two resulted from contact with the power or fuel supply for the welding apparatus; and the remaining one resulted from contact with the welding apparatus itself. The authors concluded that most of these accidents were preventable.

Three fatal accidents in which welders died as a result of falls at construction sites were described by NIOSH in 1990 and 1991 (Refs. 146, 147, and 148). In two of the incidents, the welders were wearing safety belts and lanyards, but neither worker was tied off. In the third incident, the welder either tripped or stepped backwards into an 18 by 24 inch skylight opening and fell approximately 20 feet.

Confined spaces are particularly dangerous because they can harbor invisible hazards, such as explosive gases or toxic chemicals, and may be deficient in oxygen. Oxygen depletion in a sealed chamber can result from rust formation or bacterial growth. While infrequent, accidents in confined spaces are often fatal. Unsuccessful rescue attempts, made by untrained persons unaware of hazards associated with confined spaces, sometimes result in multiple fatalities. To illustrate the dangers of such conditions and to stress the need for properly training workers who may encounter confined spaces, Rekus (Ref. 169) reviewed three accidents involving welders. The first occurred on a barge. A worker entered a cargo hold which had been sealed for 10 years and was overcome by insufficient oxygen. He was observed floating face down in the water in the bottom of the hold by two other workers who successively entered and were also overcome by lack of oxygen. Finally, a supervisor trained in rescue techniques arrived at the scene, donned a self-contained breathing apparatus, and removed the three men from the hold. The two earlier rescuers died and the original entrant eventually recovered consciousness, but he suffered brain damage.

In a similar accident, which took place on an oil drilling rig, a welder cut open and entered a tank which had been sealed for several years. The welder overcome, presumably, by lack of oxygen, fell face down in the muck at the bottom of the tank and drowned before he could be rescued. Two men, who entered the tank in an attempt at rescue, were also overcome but were later revived by coworkers. In the third case reviewed by Rekus (Ref. 169), a mechanic and a welder working inside a stainless steel chemical tank used plant air for ventilation. Unfortunately, this “air” contained only 10% oxygen. Normal air contains 21% oxygen, and the minimum safe oxygen concentration is 19.5%. The two workers collapsed from insufficient oxygen and were not rescued in time to prevent their deaths. The standby man who entered in an attempt at rescue was also overcome, but he regained consciousness and escaped unharmed.

Rekus (Ref. 169) concluded that the principal safety and health problems from welding in confined spaces are physical hazards, such as those discussed by Trent and Wyant (Ref. 203), as well as those peculiar to tanks and other enclosed spaces. Paramount among his recommendations was evaluation of the atmosphere inside a confined space from the outside, using instruments to detect oxygen levels and toxic or combustible gases, before attempting to enter.

Shaikh and Bhojani (Ref. 182) surveyed occupational injuries among 36 oxyacetylene torch welders engaged in roadside repair of automobile mufflers in Pakistan. The welders had suffered a total of 340 injuries during the three months prior to the survey. Of these, 124 were caused by foreign bodies in the eye, 55 were facial injuries, and 161 were burns. Only 16 of the welders wore goggles, and no other protective devices were used.

Accidents in which the worker is struck or crushed by the robot arm are the major hazards associated with robotic welding. While performing welding operations, the robotic welding arm does not typically move at rapid speeds. However, the arm may move at a rapid and dangerous speed in nonwelding maneuvers, such as positioning and cleaning the gun. To prevent such accidents, it is essential that personnel be kept out of the robot's working envelope. On occasions which necessitate entry into the robot enclosure (i.e., for cleaning, maintenance, reprogramming and adjustment), a combination of fail-safe design and administrative controls must be put in practice to assure that the robot is immobilized. Mangold (Ref. 130) described the various types of robot systems which are in use for welding and categorized them according to level of risk. The majority of welding robots in current use are articulated electric drive arc welders. Gantry robots, which have very large work envelopes, bear the greatest potential for accidental injury.

Bussenius (Ref. 44) reviewed the dangers to welders and other workers repairing and maintaining tanks containing combustible liquids and gases. He developed formulas predicting rates of loss of fluids from pressurized and unpressurized tanks. Safe working distances were then calculated based upon the rates of loss of the fluids and their flash points.

8.4 Stress. Valente and Chiapperini (Ref. 209) measured the pulse rate, blood pressure, oral temperature, and perspiration rate of four welders involved in fabrication of a locomotive. In addition to these physiological parameters, they also evaluated the microclimate in which the welders worked, measuring wet bulb temperature and the surface temperatures of the welders' hands and tools. They found that the welders were not subjected to excessive physical stress, but concluded that welding risks are increased by hot working conditions, leading to increased metabolic rates among welders.

Richter (Ref. 170) evaluated the physical and psychological stress experienced by 12 electric arc welders in a large chemical plant in the GDR. Pulse and respiratory rate were measured throughout the shift and recorded by telemetry. Each welder also wore a microclimate monitor under his clothing which recorded skin temperature and relative humidity. These measurements were correlated with observations of the welders' work activities. The pulse rates of the two welders with the highest pulse rates were greater than 120 during the work shift, which corresponded to a GDR work hygiene rating at which adverse health effects are "almost certain."

Psychological stresses were attributed to the necessity to exercise extreme caution during welding, the meticulousness of the work, lack of communication with coworkers, lack of visual distractions, and the repetitive nature of the work. Physical stresses included extremes of air temperature and humidity, awkward work postures, lengthy contractions of muscle groups, and exposure to fumes, gases and UV radiation.

Hyytiainen and Uutela (Ref. 97) studied work factors related to psychological stress among a group of Finnish manual workers which included a large number of welders. Problems of work organization (monotony, accelerated pace, restlessness, and fear of errors) were statistically ($p = 0.001$) related to stress among these workers, as were ergonomic factors. A significantly smaller fraction of welders reported experiencing stress than did clerical employees in the same factory and shipyard.

In a survey of occupational stresses conducted in Sweden in 1990, the mental stresses associated with welding were rated very high compared with over 100 other occupations, while physical stresses were rated only slightly greater than average. A finding of "high work load with low self-determination (little opportunity to influence one's own work situation)" was also greater than average among welders (Ref. 75). Gerhardsson (Ref. 75) noted that this combination of factors has been linked to increased incidence of cardiovascular disease, nervous symptoms, and fatigue.

Section Two
Effects of Welding on Human Health

9. Respiratory Tract

9.1 Pulmonary Function and Bronchitis. Tests of lung function are frequently used as measures of the health status of the lungs. Many of these tests can be performed with a simple instrument, the spirometer, which measures volume and flow rates of exhaled air. Forced vital capacity (FVC) is the maximum volume that can be exhaled after a maximal inhalation. The volume exhaled with maximum effort in one second is called the forced expiratory volume (FEV_1). The FEV_1 is normally about 80% of the FVC. In restrictive lung diseases, such as pulmonary fibrosis, both the FVC and the FEV_1 are reduced, but the ratio between the two (FEV_1/FVC) is normal or slightly increased. In obstructive lung diseases, such as bronchial asthma, the FEV_1 is reduced to a greater extent than the FVC, giving a lower than normal ratio of FEV_1/FVC. Other frequently measured lung function parameters are forced expiratory flow rates (FEF), FEF from 25 to 75% of FVC ($FEF_{25\text{-}75}$), and terminal flow ($FEF_{75\text{-}85}$) which are indicative of impairment in the small airways. Subnormal or declining values of Peak expiratory flow rates (PEFR) are regarded as symptomatic of asthma. These tests are rarely used for definitive diagnosis of disease in patients, but they are useful for following the progress of disease or for epidemiologic assessments of groups of workers exposed to known or suspect pulmonary irritants. The contribution of welding fumes and gases to the development of pulmonary function deficits and respiratory disorders such as bronchitis remains uncertain, and conflicting results have been reported by different investigators.

In 1979, Cotes et al. (Ref. 52) published the results of a cross-sectional survey of respiratory symptoms and lung function in 609 shipyard workers from northeast England. The incidence of chronic cough and breathlessness on exertion was related to both current smoking and the proportion of time spent working in confined spaces as a welder or caulker/burner. Lung function impairment among nonsmokers was related to employment as a welder or caulker/burner.

In a follow-up study conducted 7 years later, Chinn et al. (Ref. 48) reassessed pulmonary function and respiratory symptoms in the same cohort. Deaths (53/609) were related to age, lung function, and smoking, but not to working as a welder or caulker/burner. Of the 488 survivors who participated in the follow-up study, 425 had retired.

Chronic bronchitis developed in 77 men during the 7 year follow-up period. This condition was significantly related to smoking but not to trade as a welder or caulker/burner. Breathlessness on exertion was associated with trade as a welder and with a history of pneumonia. The welders and caulker/burners were combined for the analysis of spirometric tests, since their demographic characteristics and lung function had not differed significantly in the earlier study. After adjustment for age, the annual decline in lung function, as measured by FEV_1, FVC, and other spirometric parameters in the 488 participants, was greater among smokers and those who had ever been welders or caulker/burners than among controls.

The average decline in FEV_1 for a nonsmoking nonwelder aged 50 was 16.2 mL/year. For a welder, the decline increased to 32.6 mL/year, and, for a welder who smoked, the average decline in FEV_1 was 50.3 mL/year, three times that for a nonsmoking worker in other shipyard occupations. The annual decline in FEV_1 was also greater in men with respiratory symptoms (bronchitis, wheezing, or breathlessness) than in those who were asymptomatic. In a sub-sample of 124 redundant workers, there was also a significant interaction between the spirometric results (FEV_1 and FEV_1/FVC) and atopy (positive response to skin tests with common allergens) or elevated serum immunoglobulin E (IgE) levels. Chinn et al. (Ref. 48) concluded that exposure to welding fumes interacted with smoking and "an atopic constitution" to produce respiratory impairment.

Bogadi-Sare (Ref. 31) examined lung function and the incidence of respiratory symptoms among 47 stainless steel welders and 59 nonwelders employed in machining and polishing stainless steel. Controls were 80 workers considered to be unexposed to irritant or allergenic pollutants in the workplace. The incidence of chronic bronchitis did not differ between stainless steel workers and controls, but complaints of dyspnea (shortness of breath) and choking were significantly more frequent among the exposed workers. The stainless steel workers showed a workplace-related, statistically significant decrease in FEV_1, FEV_1/FVC, and other ventilatory parameters indicative of bronchial obstruction. Smoking did not contribute to differences between stainless steel workers and controls. Contrary to the findings in other studies, there were few significant differences in the spirometric parameters between similarly exposed smokers and nonsmokers. Bogadi-Sare stated that there was no difference in lung function between the welders and the other stainless steel workers, but data to this effect were not presented. It was concluded that stainless steel dust is an important cause of respiratory obstructive disorder in industrial workers.

Kilburn and Warshaw (Ref. 111) examined the effects of welding on pulmonary function in 226 male electric arc welders in the midwestern United States. The subjects had welded for an average of 21.3 years. They had no shipyard exposure and showed no radiographic signs of asbestosis. Information concerning occupational exposures and respiratory symptoms was obtained by questionnaire. Nearly 20% had chronic bronchitis, and 11.3% had a history of asthma; the incidence of these conditions was the same in smoking and nonsmoking welders.

The performance of this group in lung function tests was compared with a historical control group representative of the population of Michigan men. After adjusting for height, age, and years of smoking, small but statistically significant reductions in lung function correlated with years of welding experience. The only significant difference observed between smoking and nonsmoking welders was a slightly larger decrement in the $FEF_{75\text{-}85}$ in smokers. Using regression coefficients derived from data collected in this study, the authors calculated that 40 years of welding would reduce the FEV_1 to 93.3%, the midflow parameter $FEF_{25\text{-}75}$ to 77.6%, and terminal flow $FEF_{75\text{-}85}$ to 62% of age-adjusted normal values in nonsmokers. In addition to declines in these parameters, there would also be a reduction in FVC in welders who smoked.

The investigators concluded that chronic exposure to arc welding gases and fumes causes airway obstruction regardless of smoking or asbestos exposure. The magnitude of the decrements in lung capacity was smaller than those attributed to asbestos exposure in a parallel study of boilermakers with shipyard exposure conducted by the same investigators (Ref. 110).

In a third study, Kilburn and Warshaw (Ref. 112) investigated whether changes in lung function occur during a workshift in workers exposed to stainless steel welding fumes. Pulmonary function and respiratory symptoms were determined in 90 male welders employed for an average of 11 years at a fabricating shop making nuclear reactor vessels. Most of the welding in this shop was done with GTAW using argon as the shielding gas. Neither respirators nor local exhaust devices were used. Air sampling was not conducted, but on the basis of impairment of visibility, fumes in the welding area were estimated to be 1 to 3 mg/m^3. Data on respiratory symptoms were obtained by questionnaire. The rate of chronic bronchitis among smoking welders was 18%, which was four to five times greater than the rate in the reference population of Michigan men who were current smokers. In nonsmoking welders, the rate of bronchitis was 20 times the rate for nonsmokers in the comparison group. There was a small but significant reduction in FVC, FEV_1, and FEF_{25-75} in smoking welders compared with the reference population while only the FEF_{25-75} was reduced in nonsmoking welders. No changes were seen in mean diffusing capacities for carbon monoxide or alveolar volumes in either group.

Pulmonary function, measured in 31 of the workers, did not change across a work shift. Included in this phase of the study were seven stainless steel welders, 14 blackplate steel welders, and ten nonwelders who worked in the welding area and had only indirect exposure to welding fumes. Pulmonary function, and chromium and nickel concentrations in blood and urine, were determined before and after the workshift, at the start of the week. Serum and urine nickel and chromium levels were higher in the study participants than in the reference population. Blackplate steel welders had no change in urine or serum chromium levels during the workday. Serum chromium levels increased by 66% during the workshift in the seven stainless steel welders. Thus, changes in chromium absorption were not accompanied by changes in pulmonary function during an 8-hour workshift.

Lukac et al. (Ref. 128) assessed functional changes in the lungs of 101 men who welded steel bridge components in an enclosed factory room in Czechoslovakia. Lung disorders were found in 32 of 64 smoking welders and in 15 of 37 nonsmoking welders. There were no nonwelding controls in this study. The severity of the lung damage was related to duration of exposure to welding fumes and to tobacco smoking. In smokers with 10 or fewer years' welding exposure, peripheral airways disorder was seen in 6 of 26 welders while another six had obstructive lung disease. Among welders with over 20 years' experience, obstruction of the central airways, indicated by decreases in FEV_1 and FEV_1/FVC, was seen in 11 of 21 smokers and 4 of 14 nonsmokers. Dust concentrations were measured in 20 work areas during one shift in this factory. The GDR allowable concentration of 10 mg/m^3 for total dust was exceeded in five of the work areas. The levels of iron, manganese and chromium, measured during CO_2-shielded welding, were within the GDR allowable limits. Two out of three measurements of fluoride concentration exceeded the GDR limit of 1 mg/m^3.

Melbostad and Ruud (Ref. 136) studied the relationship between lung function, respiratory symptoms, and exposure duration in 164 welder/plate workers and 134 machine workers in a mechanical production plant. Respiratory symptoms, as determined by questionnaire, were significantly more prevalent in welders than in machinists. Multiple linear regression analysis showed a significant reduction in FEV_1/FVC with years of smoking and grinding but not with years of welding.

Rossignol et al. (Ref. 176) measured FEV_1 and FVC in 298 male welders and burners working in 31 metal manufacturing plants. FEV_1/FVC was the only measure of lung function significantly related to number of years working (seniority) as a welder/burner. FEV_1/FVC increased 1.8% for each 10 years of seniority. FEV_1/FVC increased by 2.7% for 10 years' seniority in workers older than the median age in the study (38.3 years), while lung function did not change with seniority in younger workers. The findings of this study are contrary to other published reports.

Kleiner et al. (Ref. 115) screened 2455 Russian workers engaged in machine manufacture for bronchitis. Of the 1794 workers exposed to metal dust or fumes, 389 were electric arc welders. The controls were 661 mechanics with little dust exposure. Chronic bronchitis was significantly more prevalent in the exposed group (24.3%) than in controls (13.6%). Compared with the mechanics, welders developed chronic bronchitis at an earlier age and after briefer employment in their trade. Twenty-nine percent of welders who smoked developed this condition, compared with 3% of those who did not smoke.

The prevalence of chronic pulmonary disease was assessed in 546 members of a Michigan boilermaker's union by Demers et al. (Ref. 53). Eighty-two percent of the study participants were welders. Because of the nature of their work, boilermakers have historically been exposed to asbestos. Since exposure levels were not available, years in the trade was taken as an indicator of overall asbestos exposure. Radiographic changes (opacities and pleural thickening), respiratory symptoms (rales, chronic cough, wheeze, chronic phlegm, and dyspnea) and pulmonary function deficits (FVC, FEV_1, and FEV_1/FVC) were statistically more prevalent among the boilermakers with increasing years in the trade. However, a statistical analysis, which included smoking status and years in the trade, did not show a positive association between welding and interstitial fibrosis or decrements in FVC or FEV_1.

Lubianova et al. (Ref. 127) reported the results of medical surveys of welders in Kiev. They found that 35% of the welders had signs of chronic bronchitis. The incidence increased with increased welding exposure, age, and smoking.

Epidemiologic studies of occupational environments are frequently hampered by the healthy worker effect, i.e., workers who become ill from occupational exposures or other causes are more likely to quit the workplace or retire early, leaving behind a population of workers that is healthier than persons of the same age in the general population. To eliminate the influence of the healthy worker effect on data concerning the contributions of occupational exposure to obstructive lung disease, Bakke et al. (Ref. 11) conducted a study of a random sample of 4992 persons from a total population of 267,304 persons in Hordeland county, Norway. The objective of that study was to obtain estimates of the prevalence of obstructive lung disease and occupational exposure to asbestos or quartz.

A second phase of this study focused on the 1512 subjects who lived in Bergen and 11 nearby municipalities (Ref. 10). A total of 1275 persons, including 84 welders, participated in this phase of the study. Each of the participants was examined for chronic cough, phlegm when coughing, and breathlessness or wheezing, which, when accompanied by a ratio of FEV_1/FVC less than 0.7, was diagnosed as chronic obstructive lung disease. Questionnaires were used to obtain data on smoking habits and past or present exposure to asbestos, quartz, wood dust, chromium, nickel, or platinum fumes, aluminum production and processing, and welding or soldering. Fifty-seven percent of the men and 2% of the women had experienced occupational exposure to one or more of these agents. Welding, along with exposure to quartz, metal fumes, and aluminum production and processing, was significantly associated with chronic obstructive lung disease and asthma [odds ratio (OR) for welding = 2.2]. The investigators cautioned that the data should be interpreted carefully because of the small number of subjects with reduced pulmonary function and because of the limited information obtained concerning occupational exposures.

9.2 Case Reports. Lee et al. (Ref. 122) examined the 35 cases of occupational asthma reported to the Ministry of Labor in Singapore between 1983 and 1990. Three of these cases were related to exposure to welding fumes (2 SMAW and 1 spot welding). The prevalence of smoking and the incidence of atopy did not differ significantly from controls. All patients were trained to use a peak flow meter and to record results. Plotting the PEFR every 3 hours during waking hours, on and off the job, for a period of 3 weeks, permitted evaluation of changes in the mean and diurnal variations. Improvement of the PEFRs during periods away from work, and deterioration of PEFRs while in the work environment, were taken as evidence of work-related airway obstruction.

One case of occupational asthma, involving a female welder who joined metal wires into a mesh for concrete reinforcement by resistance spot welding, was reported in detail (Ref. 121). This welder worked in a well-ventilated area; lubricating oil was the only chemical used in the vicinity. She welded mild steel with copper electrodes containing 0.4% chromium. Nickel, chromium, cobalt, and cadmium were not detected by environmental monitoring during the spot welding process. Clinical examination showed allergy to house dust and nonspecific bronchial hyperreactivity. Patch skin testing did not show reactivity to specific metals. Peak expiratory flow was measured at home and at work for about one month. The PEFR improved during days spent at home and deteriorated during days spent at work. When she was transferred to a nonwelding job in the same plant, there was no difference in peak expiratory flow between periods at home and at work.

A case of siderosis (iron deposits in the lung) in a man who had welded for 30 years was described by Lasfargues et al. (Ref. 120). While "reticulo-micronodules" were seen in chest x-rays, pulmonary function was normal, and there were no clinical signs of disease. Numerous hemosiderin-laden macrophages were noted in bronchoalveolar lavage (BAL) fluid, and analyses of biopsy tissue revealed patchy interstitial fibrosis. The investigators suggested that siderosis is not as benign as previously thought and concluded that this welder may have developed fibrosis as a result of siderosis, even in the absence of exposure to crystalline silica. Because many materials can cause pulmonary fibrosis, and pulmonary iron deposits are generally considered to be non-fibrogenic, it is important to rule out all suspect exposures or the presence of nonferrous fibrous or fibrogenic materials in the lungs before drawing such a conclusion.

A man who worked as a plasma arc welder was diagnosed with chronic bronchitis 12 years after he had started welding. He continued welding for 3 more years and then was placed in a series of nonwelding jobs, during which time the severity of his bronchitis continued to increase. He died of heart failure at age 57, seven years after quitting welding. A survey of the workplace atmosphere had been performed in 1974, in the midst of his welding experience. Aluminum trioxide, iron oxide, and manganese dioxide were well in excess of the GDR industrial standards at the time, but copper and Cr(VI) were below the GDR standard. On that occasion, his workplace was given an industrial hygiene rating indicative of a condition in which harmful effects or loss of productivity were almost certain to occur (Ref. 217).

Autopsy revealed mixed dust pneumoconioses, chronic tracheobronchitis, and massive emphysema. Histopathologic examination showed darkly pigmented deposits, particularly in the perivascular area, and free-floating coarse granular material in the alveoli. Chemical analysis of lung tissue showed the following concentrations of metals per gram of tissue:

Iron	12,300 µg/g	Nickel	600 µg/g
Aluminum	10,400 µg/g	Manganese	90 µg/g
Chromium	980 µg/g	Copper	30 µg/g

According to Wagner et al. (Ref. 217), these values were all at least ten-fold greater than those found in the general population.

A routine chest x-ray revealed small, bilateral nodular shadows and a cavity in the left apical area of the lungs of a 43-year old Japanese welder examined by Kishimoto et al. (Ref. 113). After a year, during which he was treated with antibacterial agents without apparent effect, a lung biopsy revealed a tuberculous lesion, pneumonoconiosis, and asbestos bodies in the left apical cavity. A mycobacterial infection (*M. kansasii*) was also found in the cavity. The pneumonoconiosis and asbestosis in this welder's lungs were considered by the authors to be an ideal culture medium for this infection.

10. Cancer

The International Agency for Research on Cancer (IARC) evaluated epidemiologic studies reported through 1989 which assessed the incidence of cancer in welders (Ref. 100). IARC concluded that "[t]here is *limited evidence* in humans for the carcinogenicity of welding fumes and gases." This evaluation indicates that a "positive association has been observed between exposure to [welding fumes] and cancer for which a causal interpretation is considered...to be credible, but chance, bias, or confounding could not be ruled out with reasonable confidence." The evidence for carcinogenicity in experimental animals was judged *inadequate* ("...studies cannot be interpreted as showing either the presence or absence of a carcinogenic effect..."), and the overall evaluation of IARC was that "[w]elding fumes *are possibly carcinogenic to humans*."

The agents in welding exposures that may be responsible for the cancer risk are not known. Stainless steel welding emissions contain hexavalent chromium, which is recognized by IARC and the National Toxicology Program as being carcinogenic in humans (Ref. 98). In addition, some forms of nickel are carcinogenic, but it is not known if the form of nickel present in stainless steel fumes is carcinogenic (Refs. 99, 133, 150, and 208). Ironically, stainless steel welders do not appear to be at a greater risk for lung cancer than mild steel welders.

In the various industrial settings in which they work, or have worked in the past, welders may have been exposed to other substances which may act alone or in combination with the components of the welding fumes to increase the risk for cancer. For example, Tossavainen (Ref. 202) pointed out that welders in foundries may have substantial exposures to materials such as silica and polycyclic aromatic hydrocarbons which could increase their risk for lung cancer. These, and other factors unrelated to the work environment, such as smoking or avocational exposures to substances which may act as carcinogens, co-carcinogens, or tumor promoters, contribute to the health status of workers and are known to confound epidemiologic studies of the cancer risk in welders.

10.1 Lung Cancer. The cohort and case-control studies considered by IARC (Ref. 100) in the evaluation of the association between exposure to welding fumes and lung cancer are listed in Tables 1 and 2. The cohort studies compared mortality from cancer in welders with cancer mortality, adjusted for age and sex, in the general population (the standardized mortality ratio or SMR) or with a specific control population (the proportional mortality ratio or PMR). In some instances, the incidence of cancer from cancer registries was used (standardized incidence ratio or SIR). The cohort studies considered by IARC are shown in Table 1. [Where a confidence interval (CI) is given, the SMR, PMR, or SIR is considered statistically significant if the lower confidence limit exceeds 100]. While most of the large cohort studies conducted in Europe and the United States showed a greater incidence of lung cancer among welders than among the control population, only one of these was significant (Ref. 186). In addition to the published studies, IARC relied upon an analysis of data combined from a number of epidemiologic studies. This analysis, published in 1990 by Simonato et al. (Ref. 184), showed a significant relationship between welding and lung cancer mortality.

The twelve case-control studies examined by IARC are shown in Table 2. Of these, two detected no excess risk of lung cancer among welders or those exposed to welding fumes (Refs. 29 and 30); four showed a moderate excess (Refs. 26, 114, 171, and 179), one of which was significant (Ref. 171); and the remaining six showed greater than a 100% excess risk (Refs. 39, 40, 76, 123, 174, and 183). The excess risk was statistically significant in four of the latter studies (Refs. 39, 76, 123, and 183). These four studies, along with the positive association of lung cancer with exposure to welding fumes seen in the majority of the cohort studies and in the data

Table 1
Lung Cancer in Welders, Cohort Studies

Reference (Country)	No. of Cases Observed	SMR, PMR or SIR	95% CI	Comments
Dunn and Weir (1968) (USA) (Ref. 56)	49	105	78–139	
Puntoni et al. (1979) (Italy) (Ref. 167)	4	125 212	34–320 58–542	Autogenous welders; two sets of standard rates used (male population of Genoa and male staff of hospital)
	3	160 254	33–466 52–743	Electric welders; two sets of standard rates used
Polednak (1981) (USA) (Ref. 164)	17	150	87–240	All welders
	7	124	50–255	Welders exposed to nickel compounds
	10	175	84–322	Other welders
Beaumont and Weiss (1981) (USA) (Ref. 23)	50	132	98–174	
McMillan and Pethybridge (1983) (UK) (Ref. 134)	5	104	34–243	PMR for respiratory cancer (three mesotheliomas)
Fletcher and Ades (1984) (UK) (Ref. 65)	8	146	62–288	
Newhouse et al. (1985) (UK) (Ref. 145)	26	113	80–157	Shipyard welders; SMR, 191 compared with general population of England and Wales (one mesothelioma)
Becker et al. (1985) (FRG) (Ref. 24)	6	95	35–207	Stainless-steel welders; expected numbers based on national mortality statistics
	6	170	70–400	Cohort of machinists used as controls (two mesotheliomas) (PMR)
Sjogren and Carstensen (1986) (Sweden) (Ref. 186)	193	142	123–163	Unadjusted SMR (four mesotheliomas)
Sjogren et al. (Sweden) (1987) (Ref. 188)	5	249	80–581	Stainless-steel welders
Tola et al. (1988) (Finland) (Ref. 199)	27	115	76–167	Welders in shipyards (SIR)
	14	142	77–237	Welders in machine shops (SIR)

Data from IARC, Ref. 100

Table 2
Lung Cancer in Welders, Case-Control Studies

Reference (Country)	No. of Cases Exposed	RR	95% CI	Comments
Breslow et al. (1954) (USA) (Ref. 39)	14	7.2	1.9–44.3	RR 7.7 adjusted for smoking
Blot et al. (1978) (USA) (Ref. 29)	11	0.7	—	
Blot et al. (1980) (USA) Ref. 30)	11	0.9	0.4–2.3	
Rinsky et al. (1988) (USA)	41	1.1	0.8–1.7	Probable welding exposure
(Ref. 171)	236	1.5	1.2–1.8	Potential welding exposure
Buiatti et al. (1985) (Italy) (Ref. 40)	7	2.8	0.9–8.5	Adjusted for smoking
Silverstein et al. (1987) (USA) (Ref. 183)	3	13.2	1.1–154.9	
Kjuuss et al. (1986) (Norway)	28	1.9	0.9–3.7	All welders; adjusted for smoking
(Ref. 114)	16	3.3	1.2–9.3	Stainless-steel welders; adjusted for smoking
Gerin et al. (1986) (Canada)	12	2.4	1.0–5.4	All welders
(Ref. 76)	10	3.3	1.2–9.2	Welders exposed to nickel
Schoenberg et al. (1987) (USA) (Ref. 179)	38	1.2	0.8–1.9	Welders or flame cutters; adjusted for smoking
Lerchen et al. (1987) (USA)	19	3.2	1.4–7.4	All welders
(Ref. 123)	6	2.2	0.5–9.1	Welders employed in shipyards
	13	3.8	1.4–10.7	Welders not employed in shipyards
Benhamou et al. (1988) (France) (Ref. 26)	18	1.4	0.79–2.9	Adjusted for smoking
Ronco et al. (1988) (Italy) (Ref. 174)	6	2.9	0.87–9.8	Adjusted for smoking

Data from IARC, Ref. 100

assembled by Simonato et al. (Ref. 184), served as the basis for the conclusion by IARC that there is limited evidence for the carcinogenicity of welding emissions in humans.

In 1985, a group of European investigators agreed to pool data from planned, or ongoing, cancer mortality studies in order to increase the statistical power of their analyses. The results were published by Simonato et al. (Ref. 184; see also the review by Moulin et al., Ref. 141). Twenty-one case-control and 27 cohort studies were included. The combined study population consisted of 11,092 male welders from 135 companies in 9 countries. The welders were categorized as "mild steel only," "stainless steel ever," and "predominantly stainless steel". Shipyard welders were placed in a separate category because of the probability of confounding asbestos exposure. SMRs were calculated using mortality data from the country in which each participating company was located.

The overall mortality of the welders was less than expected as compared with the reference populations, consistent with the "healthy worker effect." Of the major causes of death, only those from malignant neoplasms were higher than expected, based on comparison with control populations. This excess (SMR = 113, CI = 100-126) was of borderline significance, and was due primarily to a significant excess of deaths from lung cancer (116 observed vs 86.81 expected; SMR = 134, CI = 110 to 160). The risk of death from lung cancer was higher in "mild steel only welders" (SMR = 178) than in "stainless steel ever welders" (SMR = 128). Deaths from lymphosarcoma (SMR = 171) and from cancers of the bladder (SMR = 191), kidney (SMR = 139), and larynx (SMR = 148) were also higher than expected, but only the excess bladder cancer was statistically significant.

Analysis of the data for the entire cohort of welders revealed no tendency for the risk of lung cancer, or any other type of cancer, to increase with time since first exposure. However, when the cohort was broken into subgroups, the lung cancer incidence tended to increase with time since first exposure in all groups except shipyard welders. This trend was only statistically significant ($p<0.05$) for the "predominantly stainless steel" group. The excess mortality from lung cancer was unrelated to duration of employment, either in the entire cohort of welders or in any of the subgroups. Estimated cumulative doses of total fume, total chromium, or hexavalent chromium were not significantly associated with mortality from lung cancer in any of the subgroups.

The presence of five cases of mesothelioma in the cohort of welders indicated that exposure to asbestos could be a confounding factor. The mesothelioma deaths were distributed among all of the occupational subgroups, suggesting that at least some welders in each category had been exposed to asbestos. In addition, the effects of tobacco smoking could not be ruled out, but Simonato et al. (Ref. 184) maintained that smoking habits were unlikely to have been the reason for differences in lung cancer rates between welders and the reference populations.

Four epidemiologic studies of the lung cancer risk in welders were published in 1990 and 1991. Becker et al. (Ref. 25) conducted a follow-up to a study originally reported in 1985 (Ref. 24). The original study showed a significant increase in cancer mortality among 1221 welders exposed to fumes containing chromium and nickel as compared with 1694 machinists who worked in the same plants and with the general population in the Federal Republic of Germany. (This work was included in the cohort considered by Simonato et al., Ref. 184). In the follow-up study conducted 6 years later, the number of deaths due to malignant neoplasms among welders was still slightly greater than expected in the general population, but this result was no longer significant (SMR = 109, CI = 82-144). The earlier study had found a significant excess of deaths from all malignant neoplasms among welders. The relative risk (RR) was 2.4 compared with machinists in the same plants. In the follow-up, the RR was reduced to 1.6, but the excess was still significant. The RR remained unchanged after adjustment for smoking. Both welders and machinists had slight, but nonsignificant, excesses of lung cancer when compared with the general population. Cancer mortality was not significantly associated with years since first exposure for any group of welders. The increased risk of lung cancer found in this study was smaller than that seen in the large international study (Ref. 184).

Steenland et al. (Ref. 192) conducted a mortality study of 4,459 mild steel welders who had worked in three midwestern United States plants from the mid 1950's through 1988 and had had no occupational exposure to asbestos or to stainless steel welding fumes. The mortality of these welders was compared with the United States population and with a group of 4,286 nonwelders in the same plants. The primary welding technique in the plants was SMAW until the mid-1960's and GMAW thereafter. Personal monitoring data, measured between 1974 and 1987, were available for the three plants. Welders were exposed to average concentrations of 6 to 7 mg/m^3 total particulate and 3 to 4 mg/m^3 iron oxide. Nonwelders working near welding areas were exposed to average concentrations of 0.5 mg/m^3 total particulate and 0.16 mg/m^3 iron oxide; these exposures were negligible compared with those received by the welders. The lung cancer rates for welders and nonwelders were not significantly different and were slightly, but not significantly, higher than those of the general population (welders' SMR = 107; nonwelders' SMR = 117). The lung cancer risk among the welders did not correlate with duration of exposure nor with time since first exposure.

Sankila et al. (Ref. 178) studied the relative lung cancer risk of different occupations in Finland by linking data from the Finnish Cancer Registry (1971 to 1980) for male lung cancer patients aged 25 through 64 years to occupational information obtained from the 1970 Finnish census. There were 57 cases of lung cancer among welders which corresponded to a statistically significant SIR for lung cancer of 150. When the cancer incidence was calculated for specific histological types of lung cancers, welders had a statistically significant elevated incidence of epidermoid carcinoma of the lung (RR = 1.97).

Gallagher et al. (Ref. 69) evaluated cancer mortality in skilled manual metalworkers in British Columbia who died between 1950 and 1984. The 125 deaths from lung cancer among metal workers corresponded to a significantly elevated risk compared with other skilled manual workers (PMR = 129, $p<0.001$). Significantly greater PMRs were also found for Hodgkin's disease (10 deaths, PMR = 226, $p<0.05$), and all cancers (358 deaths, PMR = 124, $p<0.0001$). Calculating PMRs within a single class of workers allowed some control over smoking rates, which were assumed to be strongly related to social class. The authors cautioned that the lack of precision in identification of cause of death and occupation is a drawback in proportional mortality studies.

10.2 Nasal and Laryngeal Cancer. Dietz et al. (Ref. 54) reviewed the recent literature concerned with carcinomas of the head and neck region and concluded that the main risk factors are chronic consumption of alcohol and use of tobacco. Occupational exposures and dietary habits were also associated with elevated cancer in this region. Two case-control studies of cancer in the nasopharyngeal region were reviewed by IARC (Ref. 100). In the first, welders in general, and stainless steel welders in particular, showed increased rates of laryngeal cancer (Ref. 154). In the second case-control study (Refs. 85 and 86), an increased incidence of nasal cancer was associated with welding, flame-cutting and soldering.

A recent German study (Ref. 2) examined risk factors for laryngeal cancer in 100 male patients hospitalized for this disease compared with 100 male patients with unrelated diseases. Daily consumption of alcohol and heavy smoking were strongly related to laryngeal cancer. Welders and burners did not show an increased risk for laryngeal cancer. The authors recognized that the small sample size limited the ability of this study to detect effects.

Opposite results were seen in a study by Yu et al. (Ref. 227), who interviewed 306 nasopharyngeal carcinoma patients and 306 neighborhood-, age-, and sex-matched controls from Guangzhou City, China. Exposure to combustion products (63 cases, 33 controls) was identified among the risk factors for nasopharyngeal carcinomas (RR = 2.4, p = 0.001). In this exposure group, 15 cases and eight controls were exposed to welding fumes, but the significance of these numbers was not reported.

10.3 Urogenital Tract Cancer. Among the studies reviewed by IARC (Ref. 100), bladder cancer was found to be significantly elevated in one case-control study (Ref. 94) and one cohort study (Ref. 186). None of the other four studies cited by IARC (Ref. 100) showed a significantly elevated risk of cancer of the urinary tract in welders. However, bladder cancer was significantly elevated among welders (SMR = 191, CI = 107-315) in the multinational European study described by Simonato et al. (Ref. 184). Kidney cancer was also elevated (SMR = 139, CI = 72-243), but this was not significant. The incidence of cancer at these sites was not related to duration of exposure nor to time since first exposure. An increased incidence of prostatic cancer was seen among shipyard and mild steel workers, but was not exposure-related.

10.4 Cancer in Children of Welders. Bunin et al. (Ref. 43) reviewed studies of the association of specific types of childhood tumors with parental employment in the metal industry. These included Wilms' tumor (a childhood kidney tumor), brain tumor, and acute nonlymphocytic leukemia. Wilms' tumor has been linked with paternal exposures to lead and hydrocarbons, and paternal welding exposures are also suspect. IARC (Ref. 100) cited three case-control studies which investigated the etiology of Wilms' tumor. The first study (Ref. 108) showed a nonsignificant excess of Wilms' tumor among children of welders; in the second one (Ref. 220), none of the fathers of children with Wilm's tumor were welders; the third study (Ref. 42) found a significantly increased odds ratio for Wilms' tumor associated with children whose fathers were in a job cluster exposed to hydrocarbons, metals, or inorganic compounds. Within this cluster, five cases and one control had fathers whose occupation was welding.

Olshan et al. (Ref. 155) conducted a case-control study of 200 children with Wilms' tumor. The results in this study were also nonsignificant, but, according to the investigators, they were suggestive of an association between paternal occupation as a welder and development of Wilms' tumor. During the preconception period, fathers of six cases and one control were employed as welders; fathers of five cases and one control were welders during the pre-natal period. Fathers of six cases and two controls were employed as welders after the babies were born.

Retinoblastoma, a malignant tumor in the retina of the eye, occurs most frequently in young children. It occurs in two forms, heritable and nonheritable. The heritable form may be familial (traceable to previous occurrence of the disease in ancestors) or nonfamilial. Epidemiologic studies have associated sporadic heritable (nonfamilial) retinoblastoma with preconception exposures of the father, and laboratory animal studies have demonstrated that most of the germinal mutations associated with this form of the disease are paternal in origin. Nonheritable retinoblastoma may result from postconception exposure of the mother and fetus.

A matched case-control study, conducted in 34 North American children's hospitals (Ref. 43), included 201 cases of retinoblastoma. Of these, 19 were familial and were excluded from the analysis, 67 were sporadic heritable, and 115 were nonheritable. Children with sporadic heritable retinoblastoma were more likely than controls to have fathers employed in the metal-working industry ($p = 0.02$) or in the military ($p = 0.04$). More cases of nonheritable retinoblastoma had fathers working in a job cluster that included welders, machinists, and paper-processing workers than did controls ($p = 0.04$). The authors pointed out that the study contained so many comparisons that any or all of the significant findings could have occurred by chance. But, since the findings for workers in the metal-manufacturing and welder/machinist/paper-processing groups corroborated earlier observations, they believed that they were less likely to be chance associations.

10.5 Cancers Associated with Electromagnetic Fields. The association between exposure to EMFs and development of cancer remains in dispute. Several epidemiologic studies have suggested an association between exposure to EMFs and leukemia and brain cancer. Data from *in vitro* studies showing that extremely low-frequency magnetic fields (ELF MFs) can have an effect upon growth and development, lends support to the hypothesis that these types of magnetic fields may act as tumor promoters (Ref. 106). On the other hand, according to Jauchem (Ref. 104), epidemiologic studies of exposed workers have produced limited and inconsistent data, "...insufficient to establish a link between [EMFs] and cancer."

Five epidemiologic studies of the relationship between exposure to EMFs and the incidence of leukemia and cancer of the central nervous system reported in 1990 and 1991 included welders in the exposed population. Bastugi-Garin et al. (Ref. 16) studied 185 cases of acute leukemia and 513 age- and sex-matched hospital controls in France. A significantly increased risk of acute leukemia was observed in workers in several occupations with EMF exposures (e.g., electrical engineering technician, furnace worker, X-ray technician), but no association was found between acute leukemia and arc welding. Another case-control study conducted in Poland by Pachocki and Gajewski (Ref. 158) compared 895 adult leukemia patients with 910 controls. Information concerning exposure to EMFs was obtained from all participants. No relationship was found between the risk of leukemia and exposure to EMFs. Persons identified as exposed to EMFs were capacitor-discharge welders, induction welders, short-wave diathermy workers, and heat sealer operators.

Gallagher et al. (Ref. 68) examined mortality data for 320,423 workers from British Columbia who died between 1950 and 1984. There was an insignificant increase in mortality from brain and central nervous system cancer in the group of selected occupations suspected of having high exposures to EMF. Although welders were considered to have a very high magnetic field exposure, they showed no elevated risk of death from brain cancer. Gallagher speculated that the inclusion of oxyacetylene welders, with presumably little or no occupational exposure to magnetic fields, could have "contaminated" the study, reducing the chances for observing an association between central nervous system cancer and exposure to EMFs during electric arc welding.

Tornqvist et al. (Ref. 201) examined the incidence of leukemia and brain tumors in Swedish workers with potential exposures to EMFs. Cases of leukemia and brain tumors, and information on their occupations, were obtained from the Swedish Cancer Environment Registry and the national census. Of the 133,687 men who had worked in occupations with EMF exposures, 21,045 were classified as welders and flame cutters. Welders and cutters showed no excess risk of leukemia; the ratio of observed brain tumors to the number expected, on the basis of the cumulative incidence in the reference population of almost 2 million Swedish working men, was of borderline significance (46 cases, SMR = 130, CI = 100 to 170). In a sub-group of welders and cutters in iron and steel works, the incidence of brain tumors was higher, but still only of borderline significance (14 cases, SMR = 320, CI = 100-740).

In a Finnish study, Juutilainen et al. (Ref. 106) determined the relative incidence of leukemia, acute myeloid leukemia, and central nervous system tumors among workers presumed to be exposed to EMF and ELF MF. The study population consisted of all Finnish males who were classified as industrial workers in the 1970 Finnish census. The cancer incidence data were taken from the Finnish Cancer Registry for 1971 to 1980. Welders and flame cutters had no excess incidence of either leukemia (5 cases vs 5.0 expected) or central nervous system tumors (8 cases vs 9.7 expected).

10.6 Cancers Associated With Ultraviolet Radiation. Ultraviolet radiation is produced during arc welding, with intensities depending upon the process and welding conditions. In addition to the UVB radiation (280 to 315 nm) associated with skin cancers from sun exposure, welding arcs and plasma torches produce UVC radiation (100 to 280 nm), a particularly damaging region of the UV spectrum. UVC is also a component of solar radiation, but it is totally absorbed by ozone and water vapor before reaching the earth. UVC has induced skin cancers in experimental animals and cell transformations in mammalian tissue cultures (Ref. 62). Cancers have also been shown to be more prevalent in areas of the skin that have been subjected to repeated trauma or erythema due to excessive heating such as may be experienced by welders (Ref. 62). Despite this evidence, skin cancer has not been shown to be associated with welding in epidemiologic studies. Skin cancer was not reported in the case-control and cohort studies reviewed by IARC (Ref. 100), but one case report of multiple epitheliomas in a welder/cutter was mentioned (Ref. 175).

Uveal melanoma is the most common intraocular malignancy in adults but few risk factors have been identified. Holly et al. (Ref. 93) conducted a case-control study in 11 states in the western United States to examine the possible role of UV light in the etiology of uveal melanoma. Included in the study were 407 patients with uveal melanoma and 870 randomly selected controls. Severe burns to the eyes from welding, sunburn of the eye, and snow blindness were grouped together, and exposure to any of these factors carried a statistically significant relative risk of 7.17 for uveal melanoma compared with the controls.

11. Metal Fume Fever

Metal fume fever, an acute illness of short duration with flu-like symptoms, is caused by exposure to high concentrations of metal oxide fumes. Metals which can cause fume fever include zinc, copper, magnesium, aluminum, antimony, iron, nickel, cadmium, and tin. A typical case of metal fume fever was described by Heydon and Kagan (Ref. 88). A farmer spent 5 hours cutting galvanized steel with a gas torch without wearing a mask. Two hours later, he developed a cough and had difficulty breathing. He felt chilled and had cramps in both legs. His symptoms resolved within a day. Other symptoms which are characteristic of metal fume fever, but were not associated with this case, include fever, nausea, headache, thirst, polyuria, diarrhea, weakness, fatigue and general malaise.

Because tolerance can develop with repeated exposure to metal fumes, metal fume fever frequently occurs on Mondays, after a weekend break from exposure. Hence, metal fume fever is sometimes referred to as "Monday fever." It is often assumed that this condition has an immunological basis, but that is uncertain. The pathogenesis of metal fume fever in humans was examined by Blanc et al. (Ref. 27) who studied cellular functions and biochemical responses to zinc welding fumes. Blanc cited previous studies which demonstrated that zinc oxide fumes, even in low concentrations, can cause marked pulmonary inflammation (e.g., see Lam et al., Ref. 118), suggesting that the metal fume fever response is initiated in the lung. This is substantiated by reports that neither ingestion nor intravenous injection of zinc will elicit fume fever in laboratory animals. Based on this, Blanc hypothesized that polymorphonuclear leukocytes (PMNs), a type of inflammatory white blood cell, responding to inhaled zinc oxide fumes, release cytokines (mediators which elicit reactions in cells or tissue remote from the cells where they originated). The cytokines, in turn, produce the systemic, flu-like symptoms characteristic of metal fume fever.

To test this idea, Blanc (Ref. 27) examined the pulmonary response of volunteers to zinc oxide fumes. Using standard eye and skin protection, but no respiratory protection, fourteen experienced welders welded galvanized mild steel with standard cellulose-covered carbon steel (cadmium-free) electrodes for 15 to 30 minutes in an enclosed chamber with controlled ventilation, temperature, and humidity. Pulmonary fluids were obtained by BAL at 8 hours after welding from five of the participants (early follow-up) and at 22 hours after welding from the remaining nine participants (late follow-up). The BAL fluid was assayed for total and differential white blood cell counts and for concentrations of two cytokines, interleukin-1 and tumor necrosis factor (TNF), deemed likely to be present following this type of pulmonary challenge.

Only minimal changes were found in pulmonary function and airway reactivity at 1, 6 and 20 hours after welding. The number of PMNs in the BAL fluid increased markedly with time after exposure and correlated positively with zinc exposure at 8 hours. The numbers of lymphocytes, PMNs and macrophages correlated positively with exposure at 22 hours. Little or no TNF or interleukin-1 was detected in the BAL fluid. The investigators recognized that a number of cytokines are released from inflammatory cells and that cytokines other than the two assayed could be responsible for propagating metal fume fever. As the authors suggested, they may have examined the wrong cytokines, and it is still possible that cytokines, or a cytokine-like mechanism, may mediate the syndrome of metal fume fever.

12. Effects on the Ear

Burns produced by flying sparks are a common ailment of welders. Burns of the ear are infrequent but can be very damaging. Mertens et al. (Ref. 137) described 25 cases of injuries to the tympanic membrane that resulted from welding sparks. In all cases, the burns occurred while welding overhead or in a bent over position in a confined space. Fisher and Gardiner (Ref. 64) described five cases of such injury which ranged from minor burns to the external ear to persistent tympanic membrane perforation and inner ear damage. According to these authors the welder's "visor" type helmets offer little protection to the ears when working in cramped conditions with the neck flexed or when working overhead. Ear protection can be improved by a drape over the head, by a lateral extension on the helmet, or by the use of nonflammable ear plugs.

13. Effects on the Eye and Vision

13.1 Cataracts. Chronic exposure to low levels of UV light, especially UVB (320 to 290 nm), has been implicated in the formation of cataracts. Lasers emitting UV radiation can induce permanent cataracts within 24 hours of exposure and can damage the retina, iris and cornea. Exposure to IR radiation from hot materials such as molten glass or steel can also cause of cataracts.

Animal experiments have shown that increases in the lens temperature by just several degrees is sufficient to produce cataracts. Okuno (Ref. 151) calculated the temperature distributions developed within a theoretical model of the human eye exposed to IR radiation. His results suggest that IR cataracts induced in the workplace result from absorption of IR by the cornea followed by heat conduction to the lens. From the relationship between the incident irradiance and the lens temperature, the threshold IR irradiances for cataract formation were determined to be in the range of 163 to 178 mW/cm^2 for exposures lasting longer than 5 minutes under normal conditions. For workers who perform heavy work at high ambient temperatures, these values may be reduced by 50%. Okuno suggested that these threshold data could be used to establish workplace exposure limits for IR radiation exposure to the eye. To protect against cataract formation, he recommended that IR irradiance be limited to 80 mW/cm^2 for exposures over 5 minutes.

In a survey of occupational injuries that occurred in a work force of 160,000 persons over a period of 23 years in the GDR, Hanke and Karsten (Ref. 83) identified four welders with cataracts. The four welders were 29 to 56 years old at the time their cataracts were diagnosed and had welded for 12 to 31 years. The IR exposures received by these men during their welding experience were estimated from detailed exposure histories and reconstruction of their workplace routines. The average number of hours per day spent welding was calculated from measurements taken during 105 typical work shifts. The intensity of the IR radiation they had received was approximated by measuring the IR radiation produced by the various welding processes they had used and calculating the energy that would have contacted their eyes, taking into consideration the types of face shields they had used and the length of time spent welding during a shift. All four welders had routinely been exposed to doses of IR radiation in excess of the maximum safe limits recommended by Okuno (Ref. 151). One of the four welders had routinely been exposed, without eye protection, to radiation from preheated materials. This source of IR radiation accounted for 37% of the calculated lifetime dose he received. Another of the welders received radiation from metal parts that remained super-heated after welding was completed. The welder did not wear eye protection, and this radiation contributed 97% of the total calculated IR radiation dose to the eyes. This man was the youngest, and also had the briefest welding experience of the welders with cataracts; but all four developed cataracts at a younger age than is common in the general population.

13.2 Photokeratitis. Shortwave UV light (270 to 290 nm) is absorbed by the outer layers of the eye and can cause photokeratitis (arc eye, welder's flash, or photophthalmia). Photokeratitis, a marked inflammation of the cornea, is the ocular condition most frequently encountered by welders. Symptoms appear between 1 and 24 hours, depending on the intensity of the exposure, and include blurred vision, headache, photophobia (sensitivity to light), tearing, and conjunctivitis. These effects normally last up to 2 days and have no sequelae.

While photokeratitis can be produced by unprotected exposure of even a few seconds to a high-intensity UV source such as arc welding, retinal damage usually results from exposures of longer duration. Power et al. (Ref. 166) described the case of a 45-year-old welding trainee who developed bilateral maculopathy (retinal injury) following unprotected exposure of less than two minutes' duration to a SMAW unit. The day after exposure, the patient experienced blind spots and distorted vision but no ocular pain. While there was no photokeratitis, an edematous lesion was noted in the macula (an area of the retina) of each eye. His visual acuity was completely restored within 6 months after exposure. The severity of the macular lesions was unusual for such a brief exposure, as was the formation of retinal lesions in the absence of photokeratitis. The investigators suggested a link between these observations and the drug fluphenazine, which the patient had taken for 10 years to treat his depression. They postulated that the drug fluphenazine accumulates in the retinal pigment epithelium, where it can act as a photosensitizing agent, making the retina particularly susceptible to photochemical damage. They cautioned that persons taking phenothiazine drugs may be at special risk of developing welding-induced retinal damage.

Neki (Ref. 144) questioned the assumption that the macular lesions were due to drug-related photosensitivity. Instead, he suggested that it is equally possible that the drug concentrated in the cornea, making it more resistant to photochemical damage and allowing the formation of retinal lesions in the absence of corneal effects. As Neki alludes to, these hypotheses are conjectural and could be tested in experiments with laboratory animals.

13.3 Eye Injury. Occupational eye injuries comprised 2.5% of all injuries treated in a Hospital in Esbjerg, Denmark, during a 4 month period in 1987. Seventeen percent of the patients with eye injuries were welders (Ref. 9). Noting that ocular foreign bodies are an occupational hazard for people working in metal processing industries, Banerjee (Ref. 13) performed a survey of patients who came to the hospital in Walsall, England, with this type of injury during a six-month period beginning in August 1989. Of the 472 patients who appeared in the emergency department with foreign body eye injuries, 164 were included in this study; 19 were welders. Most of the patients surveyed were employed by the many metal processing plants in the vicinity of Walsall. For 136 of the participants, the injury was sustained while doing their usual jobs in the workplace. Sixty-five had not been using the eye protection required by British standards. Since the data were not broken down in terms of occupation, it is not possible to discern whether the welders were among those using eye protection, or even if they were injured while welding.

A survey conducted by Ten Kate and Collins (Ref. 198) also related eye injury to the use of appropriate eye protection, but the population studied by these investigators was restricted to welders. The welders selected for this study did not necessarily seek medical care for their injury, so less acutely serious eye injuries were recorded. Welders were queried by two routes: 87 were interviewed directly by one of the investigators, and 41 responded to questionnaires sent by mail. Participants were asked about the number of "flashes" received, or ocular or systemic symptoms experienced during the week prior to receiving the questionnaire. These data were related to the type of welding conducted, use of eye protection, and welding history. Forty percent of the welders reported "receiving at last one welding flash." Nine oxyacetylene welders welded without eye protection during the previous week, but only one of them worked this way for more than an hour. Unprotected exposure to nearby welding was experienced by 64% of the welders. Eighty-five percent of the welders thought their eye protection was in compliance with Australian standards; the remainder were unsure. Reports of eye symptoms (e.g., tired, sore, watery or itchy eyes) correlated well ($p<.001$) with the number of flashes received. Blurred vision was experienced by 27% of the welders, and back pain, headache, and neck pain were reported by about one-third of the respondents.

Narda et al. (Ref. 142) studied the incidence of chronic conjunctivitis over a 10-year period in arc welders working in a foundry in Italy. The study included 41 welders; 31 performed SMAW and 10 performed submerged arc welding. Airborne dust levels in the foundry often exceeded the ACGIH TLV of 10 mg/m^3 for total dust. The frequency of chronic conjunctivitis was substantially higher among the welders than among controls (RR = 4.25). The incidence of conjunctivitis was 49.8% in the exposed group. Shielded metal arc welders had a higher incidence (56.9%) than did submerged arc welders (32.4%). Ocular symptoms (eye burning, tearing, photophobia) often occurred before the development of conjunctivitis. The investigators concluded that findings of a prevalence of ocular symptoms should lead to careful examination of the working environment.

13.4 Long-Term Effects. To explore the effects of long-term welding exposure on the cornea, Norn and Franck (Ref. 149) examined the outer part of the eye in 217 male welders from two factories in Denmark. The most striking finding was the presence of spheroid degeneration in 24% of the welders, compared with 4% in a control group of nonwelders. This disorder is characterized by small (30–40 μm), globular, limpid, yellowish or brownish lesions on the exposed part of the conjunctiva or cornea. A significant, but much smaller, increase in the incidence of pinguecula (yellow spots on the exposed conjunctival bulbi) was also noted. Corneal cicatrices (small scars on the cornea) were present in about half the subjects. The incidence of these three types of lesions increased with increasing welding exposure. Pterygium, a UV light-induced membranous growth on the outer eye, was not related to welding in this study, as it was found in only one welder and no controls.

13.5 Contact Lenses. The dangers of wearing contact lenses while welding have long been debated. Rumors that radiation from the welding arc could cause the lens to fuse to the cornea, potentially causing blindness, stem from an incident which occurred in Baltimore in 1967. At that time, an arc welder at Bethlehem Steel Corp. was exposed to an explosion at an electric switch box while he was connecting a welding instrument to a 440 Volt grid. The welder was wearing contact lenses and safety glasses at the time of the incident. Following the incident, he suffered temporary injury to the corneal epithelium. The attending physicians determined that the injury was unrelated to his exposure to the electric flash. Instead, they attributed the injury to failure to remove the contact lenses for 17 hours following the incident. Reports of this incident soon became distorted, and the injury was described in American and international journals and news media as a fusion of the lens to the cornea caused by exposure to the welding arc. These and other reports of blindness or vision loss resulting from wearing contact lenses while welding have led to widespread company policies forbidding welders to wear contact lenses.

Several articles disputing such policies were published during the current report period (Refs. 77, 125, 168 and 222). Winkleman (Ref. 222) wrote in response to two recent publications in the GDR which claimed that recent research presented new evidence of health risks associated with wearing contact lenses while welding. Giroux and Remba (Ref. 77) and Loriot and Tourte (Ref. 125) reviewed the literature on this subject. They described conclusions drawn by a study group sponsored by the French National Institute of Research and Safety and an extensive investigation conducted by the American Optometric Association. The latter investigation showed that reports that a welding arc or electrical spark caused fusion between the contact lens and the eye lack scientific validity. The general conclusion of both groups was that, when proper safety eyewear is worn over contact lenses, the use of contact lenses adds no further risk to injury from exposure to the welding arc.

14. Effects on the Skin

Ultraviolet light, generated by electric arc welding, can cause erythema (e.g., sunburn) on unprotected skin. Ultraviolet radiation can be reflected by some surfaces and reflected UV light, is still capable of causing erythema or other forms of UV-induced injury. Hindsen et al. (Ref. 92) described a case where a welder developed mild facial erythema even though he wore a welding helmet. Simple detective work showed that the erythema developed after he started wearing a white textile hood in addition to the helmet. The erythema, which was attributed to UV radiation reflected from the white hood, could be prevented by a sunscreen or by the use of black cloth.

Young et al. (Ref. 226) described a welder who had recurrent facial dermatitis associated with welding. The dermatitis disappeared when he was not welding and recurred within 1 day after returning to the job. Skin testing revealed no allergies related to work place exposures but other tests showed an abnormal reaction to UVC and UVB radiation and mildly abnormal reactions to UVA radiation. A shield was used while welding so the investigators concluded the reaction was due to indirect exposure to UV radiation.

15. Effects on the Nervous System

Sjogren et al. (Ref. 189) conducted a study of neuropsychiatric symptoms among welders which focused on effects of lead, manganese, and aluminum. Lead and manganese have well established neurologic effects. Chronic exposure to manganese can cause behavioral changes, psychosis, and a Parkinson-like syndrome. Acute exposure to lead has been associated with encephalopathy, and chronic exposure has been associated with peripheral neuropathy, chronic encephalopathy, and other neurobehavioral disturbances (Ref. 124). Studies in kidney dialysis patients (see citations in Sjogren, Ref. 189) and in animals (Refs. 22, 116, and 195) have implicated aluminum as a neurotoxin. Aluminum is not well absorbed, is usually cleared through the kidney, and is not known to cause neurological disorders in healthy individuals. However, in patients with reduced renal function, it may accumulate and become a problem (Ref. 139).

The study cohort consisted of 65 welders who welded primarily aluminum and 217 railroad track welders. One third of the railroad track welders had welded lead-painted steel and high-alloy manganese, exposures less common among the aluminum welders. Eighty-five percent of the aluminum welders and only 48% of the railroad track welders had welded for more than 10 years. Information on exposures to welding fumes, disturbances of memory and concentration, affective changes, and symptoms of vegetative nervous system dysfunction was obtained by self-administered questionnaires. Subjects who welded aluminum, lead, or manganese for long periods experienced significantly more neuropsychiatric symptoms than welders exposed to chromium or nickel. Depression and difficulty in concentrating were associated with exposure to aluminum fume. Short memory, forgetfulness, and frequent headache were associated with welding lead-painted steel. Experiencing painful tingling sensations was associated with exposure to manganese fume. These results should not be considered conclusive because (1) data on exposure to other neurotoxic agents (e.g., organic solvents, alcohol) were not collected in this study and (2) the analyses were done strictly by questionnaire. As the authors suggested, detailed psychometric studies should be performed on welders exposed long-term to specific metals to “verify or refute these results”.

The etiology of Parkinson’s disease is not understood, but some authorities believe it is linked to environmental factors (Ref. 196). Chronic exposure to manganese can cause a progressive disease, which in advanced stages resembles Parkinson’s disease, with muscle weakness, muscle rigidity, tremors, and impaired gait. Wechsler et al. (Ref. 218) reported the results of a pilot study undertaken to evaluate a broad range of occupational and environmental agents for potential associations with Parkinson's disease. The study compared 34 Parkinson's disease patients (average age 68.4 years) with 22 neurology clinic patients (average age 58.9 years) with other disorders. A self-administered questionnaire was used to collect data concerning occupation, well-water use, pesticide use, metal exposures, medical history, smoking, alcohol consumption, and drug use.

Analysis by metal exposure in males indicated more frequent exposures to aluminum and copper. Three of the male Parkinson's disease patients and none of the controls had been employed as welders. The three welders reported exposures to aluminum but not to other metals. None of the Parkinson's disease patients reported exposure to manganese, mercury or nickel whereas one of the controls had mercury exposure. Analyses of metal exposures were limited to males because too few of the females in the study reported such exposures. Thus, the number of cases considered was extremely small (19 male Parkinson's disease cases vs 9 controls) and the results were not statistically meaningful.

Armon et al. (Ref. 7) conducted a case-control study to evaluate risk factors for amyotrophic lateral sclerosis (ALS), an uncommon degenerative disease of the motor neurons. Occupational and recreational data were collected for 47 male patients and 47 corresponding patient controls. Men with ALS had spent significantly more time welding or soldering than controls ($p<0.01$). The type of welding or soldering, and the materials worked with, were not investigated. ALS patients had a greater exposure to lead than did controls ($p<0.05$). Because the latter results fit in well with data that had been previously reported, the investigators concluded that their results suggested an association between ALS and exposure to lead vapor.

16. Effects on the Immune System

Ulrich et al. (Ref. 207) examined absorption of metals and changes in serum proteins in welders who conducted GMAW with a CO_2 shield. Air concentrations of total particulate in two welding areas were 5.4 mg/m^3 and 6.3 mg/m^3; 30% of the measurements were over 10 mg/m^3. The levels of Co, Cd, Cu, Cr, Mn, Ni, and Fe were measured in hair samples from 69 welders and 47 controls. Cr, Mn, Ni, and Fe were significantly elevated ($p<0.001$) in welders. There was a positive association between the number of years spent welding and the level of Mn, Ni and Fe. Serum levels of immunoglobulins IgG, IgA, and IgM were measured as indicators of the activity of the immune system and various serum proteins were measured as indicators of inflammation in 97 welders and 36 controls. Significant changes in humoral immunity were seen in the welders; IgG increased, and IgM decreased with the duration of welding. Likewise, the serum indicators of inflammation, complement and alpha-1-antitrypsin, changed significantly with the number of years welding experience.

17. Effects on the Musculoskeletal System

Welding often requires sustained effort in awkward postures while handling heavy equipment, resulting in static stress on the arms and shoulders. While this stress occasionally results in traumatic injury, chronic disease is more common. Torner et al. (Ref. 200) evaluated the effects of welding on the musculoskeletal system by comparing the frequencies of physical disorders in 58 licensed Swedish shielded metal arc and gas tungsten arc welders and 33 office clerks from the same energy equipment production plant. Information concerning subjective symptoms was obtained by questionnaire. Objective evaluation of musculoskeletal disorders was determined by orthopedic examination. Figure 3 illustrates the frequency with which confirmed physical disorders and subjective symptoms were detected in different parts of the musculoskeletal system. Both physical abnormalities and subjective symptoms were more prevalent among the welders than among the clerks. The excessive shoulder level work performed by welders at this plant was reflected in the incidence of neck and shoulder symptoms; 76% of the welders compared with 36% of the clerks reported having experienced neck and/or shoulder symptoms during the previous year. This was confirmed by clinical examinations which showed that the range of motion in external rotation of the shoulders was significantly less among the welders than among the clerks. Almost half the welders had atrophied shoulder muscles, the supra- or infraspinatus muscles being the most severely affected. The muscular atrophy correlated with a decrease in 90° arm abduction strength.

Subjective knee symptoms and clinically confirmed bursitis in the knee were significantly more prevalent among welders than among controls. This was attributed to the large amount of kneeling required of the welders. Most of the welders (60%) considered their symptoms to have been caused by heavy work for a prolonged time, while only 12% attributed their musculoskeletal symptoms to a sudden traumatic incident at work. This was in accord with the finding of Hyytiainen and Saarela (Ref. 96) that only a small number of welders attributed occupationally related lower back pain to "sudden movement."

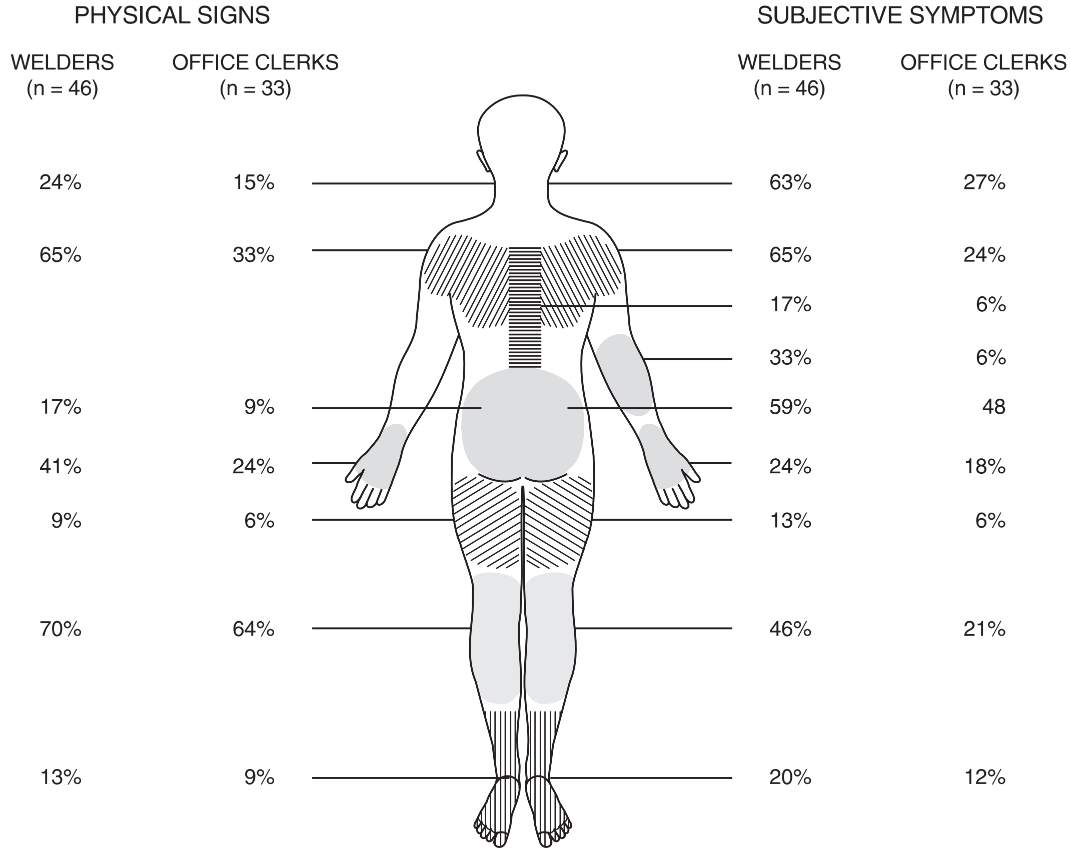

Figure 3—Frequency of Physical Symptoms Affecting Different Parts of the Musculoskeletal System (Indicated by Solid Lines). The Proportion of Workers Who Had Experienced Symptoms During the Previous 7 Days, or Who Had Been Forced to Reduce Their Daily Activity as a Result of Physical Symptoms During the Previous 12 Months, is Indicated. Torner et al., Ref. 200

Hyytiainen and Saarela (Ref. 96) surveyed risk factors for accidental lower back injuries in 3500 persons employed in a shipyard and 700 workers employed in a metal products manufacturing plant. Risk factors for accidental back injuries were identified by questionnaires, observation, and insurance company accident reports. Five of the eleven insurance company reports involving lower back injuries in welders were attributed to lifting, another five were due to stumbling, slipping, or falling, and the remaining injury was caused by "sudden movement." The major risk factors for accidents involving lower back injuries identified by the welders in response to a questionnaire were prolonged/awkward working postures (44%) and incorrect heavy lifts (29%).

In a later study, Hyytiainen and Uutela (Ref. 97) explored the relationship between job stress and lower back pain. Data were obtained by questionnaires sent to a group of manual workers (182 welders, 197 plumbers and 125 sheet metal workers) and 170 clerical workers from a ventilation equipment factory in Finland. Ergonomic factors (e.g., prolonged sitting and standing, confined work space, and awkward work postures) had the greatest influence on the development of lower back pain among the manual workers. But nonphysical factors (hurry, monotony, and an accelerated working pace) were also related to lower back pain.

Jarvholm et al. (Ref. 103) used simultaneous measurement of intramuscular pressure and electromyography (tracings of the electrical changes which accompany muscular activity) to study the effectiveness of an arm support in reducing the load on the supraspinatus muscle of the shoulder during simulated welding operations. Although both methods demonstrated that the arm support achieved a significant reduction in the supraspinatus muscle load during low- load assembly work and high-load welding applications, the muscle pressure was still high enough during the simulated welding operation to reduce blood flow in the muscle. The authors concluded that arm support greater than the 2.2 to 3.4 pounds (force) used in this study would be needed to reduce intramuscular pressure sufficiently to lower the incidence of shoulder pain and muscular injury.

Marciniak and Badowski (Ref. 132) reviewed 28,324 X-rays of the spine of job applicants and workers in a Polish automobile factory. A high incidence of vertebral epiphysitis (inflammation of vertebrae: 22.5%) and scolioses (curvature of the spine: 10%) was noted among the 17- to 21-year-old job applicants. Statistical analysis showed that at age 40, static changes in the spine were more strongly related to pre-existing vertebral epiphysitis than to the character of the work performed. However, the highest incidence of scoliosis was found among workers in jobs involving the greatest spinal loading, i.e., tinsmiths, pressers, and welders.

Carpal tunnel syndrome (CTS) results from nerve damage caused by compression of the "carpal tunnel" formed by the carpal bones of the wrist. This section of the wrist is illustrated in Figure 4. CTS can result from repetitive wrist movement tasks such as welding (Ref. 160) or from use of vibrating hand-held tools (Ref. 82). The symptoms of CTS can range from numbness and tingling in the hands, to wrist pain, and disability. Hagberg et al. (1991) conducted a study of 41 workers who had required surgery to correct the effects of CTS. Welding was one of the four most common occupations among the CTS patients. Panio (Ref. 160) stressed that prevention of CTS is possible with the cooperation of management, supervisors, and workers. He recommended a program that includes pre-employment screening to determine those who already have CTS symptoms; education to make workers aware of causes and preventive measures; modification of job routine to reduce

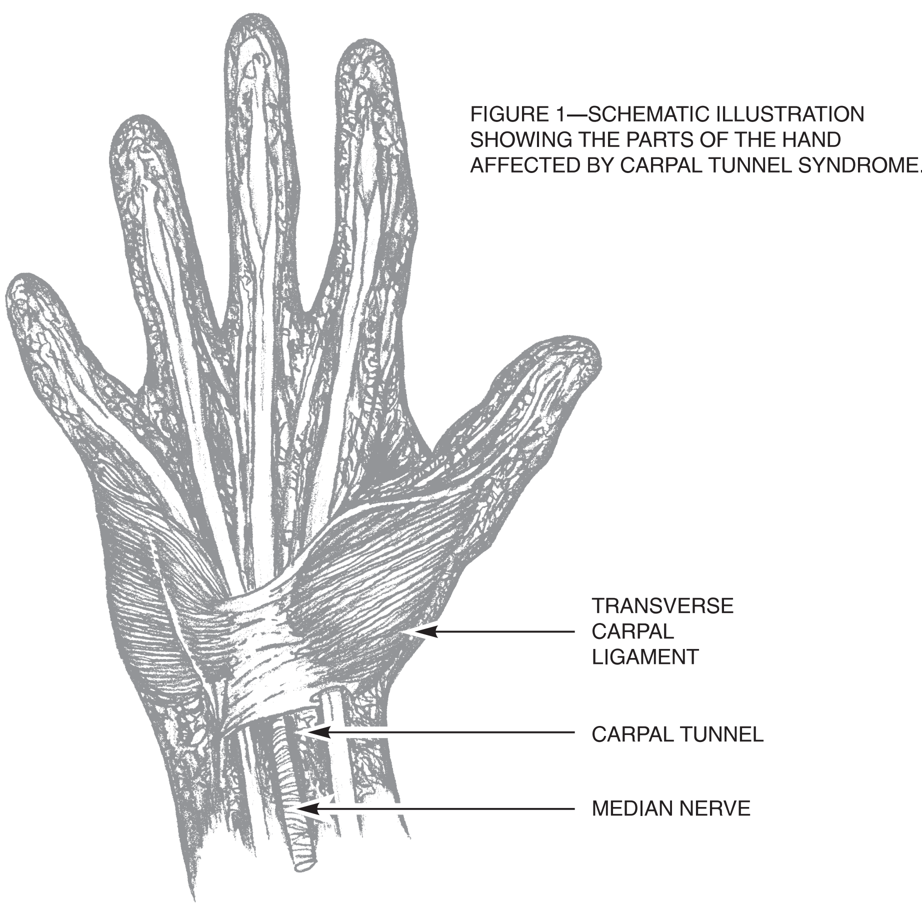

Figure 4—Drawing of Hand Showing Location of Carpal Tunnel and Position of the Median Nerve Affected by Carpal Tunnel Syndrome. Panio, Ref. 160

unnatural angles of the wrist; special gloves or braces to maintain correct wrist alignment; and tool modifications, such as curved-handled welding guns.

18. Effects on the Kidney

18.1 Cadmium. Chronic exposure to low levels of cadmium fumes can cause kidney damage. Proteinuria, the urinary excretion of low molecular weight (LMW) serum proteins such as beta-2-microglobulin, is often the first symptom of kidney damage and is generally thought to result from damage to the kidney tubules. In 1984, Chiesura, Trevisan, et al. (Ref. 47) reported the results of studies of 16 persons from workshops where brazing was performed with high-cadmium alloys. Beta-2-microglobulin and other proteins indicative of tubular dysfunction were present in urine samples from some of the workers who had no frank indications of kidney damage.

In a follow-up of that study, Trevisan and Maso (Ref. 204) re-examined six of the welders who had been exposed to high cadmium levels before they ceased welding in 1982. Excretion of LMW proteins typical of tubular dysfunction, and serum and urinary cadmium, were determined annually in each of the welders for the first 5 years after they ceased welding. Cadmium levels in urine and serum decreased steadily in all six subjects during the 5-year follow-up period (Figure 5a and 5b). Three of the subjects had shown no indications of LMW proteinuria while welding, and their urinary protein levels remained low during the 5-year follow-up period. The remaining three welders had shown LMW proteinuria (beta-2-microglobinuria), and one of them also had developed total proteinuria, while still exposed to cadmium.

During the follow-up period, beta-2-microglobinuria increased up to a maximum in two of these welders, while in the third there was a temporary increase in beta-2-microglobinuria which returned to normal levels after 5 years (Figure 5c). Total protein was only elevated in the welder who had had this condition while exposed to cadmium. These results indicate that tubular dysfunction may be reversible in some, but not all, persons with this cadmium-induced condition.

18.2 Chromium. While acute kidney disease can result from massive exposure to chromium, chronic renal disease resulting from occupational or environmental exposure to chromium has not been reported. Based on published literature, Wedeen and Qian (Ref. 219) developed an argument for the possibility that long-term exposure to chromium can induce chronic kidney disease. Occasional cases of acute tubular necrosis following massive absorption of chromate have been described in man. In experimental animals given large doses of hexavalent chromium compounds, chromate selectively accumulates in the convoluted proximal tubule and causes necrosis. Wedeen surmised that long-term exposure to low levels of chromium could also cause chromate accumulation in the kidney tubules of humans, resulting eventually in kidney damage. Such damage should be evidenced by the findings of LMW proteins in urine. In this regard, studies of urinary proteins in chromate workers have yielded conflicting findings. Wedeen cited one study in which LMW proteinuria was found in chromium workers (Ref. 66). However, other studies have not associated LMW proteinuria or other indicators of renal function with long-term chromium exposure in welders [Refs. 215 and 231). In addition, as Wedeen pointed out, LMW proteinuria occurs after a variety of physiologic stresses, is usually reversible, and cannot by itself be considered evidence of chronic renal disease. Nonetheless, Wedeen maintained that since high-level chromate exposure can induce acute tubular necrosis, and since one study showed LMW proteinuria in chromium workers, there is a strong need for large-scale, prospective case-control epidemiologic studies to demonstrate whether or not delayed renal effects can result from low-level, long-term exposure to chromium.

19. Fertility

Boshnakova and Karev (Ref. 37) examined the risk of spontaneous abortions and stillbirths (“reproductive failures”) among families of welders. Data were gathered by questionnaire from a study population consisting of 72 welders and 41 controls. Reproductive failures occurred in families of 15.3% of the welders and 9.8% of the control group. Fetal deaths occurred earlier in the pregnancy among welders families than among controls. Thus, spontaneous abortions occurred significantly more frequently in the group of welders and still births occurred significantly more frequently in the control group.

Bonde (Ref. 32) conducted a case-control study of the association between welding exposure and delayed conception (subfertility), defined as “no conception within at least 2 years of unprotected intercourse”. The study population consisted of 432 male welders and 240 nonwelding male metal workers and electricians from six plants in Denmark. Data concerning reproductive experience, occupational exposure, and medical history were obtained by self-administered postal questionnaires. The response rate was 79% for welders and 83% for nonwelders. A significantly increased risk for delayed conception was observed among the welders.

In a continuation of this study, Bonde et al. examined fertility in a Danish cohort of 3702 male metalworkers (Ref. 35). The subjects were employed at 74 stainless steel and five mild steel factories for at least 1 year

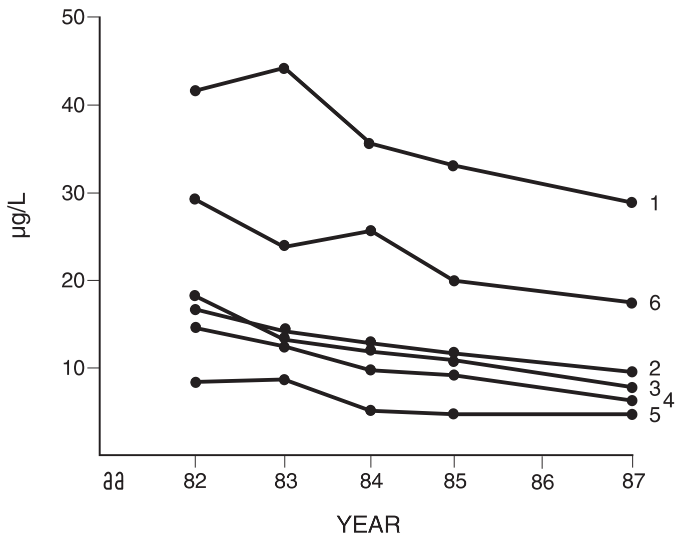

Figure 5A – Cadmium Levels in Serum from Six Welders During the First 5 Years After Exposure to Cadmium Ceased. Trevisan and Maso, Ref. 204

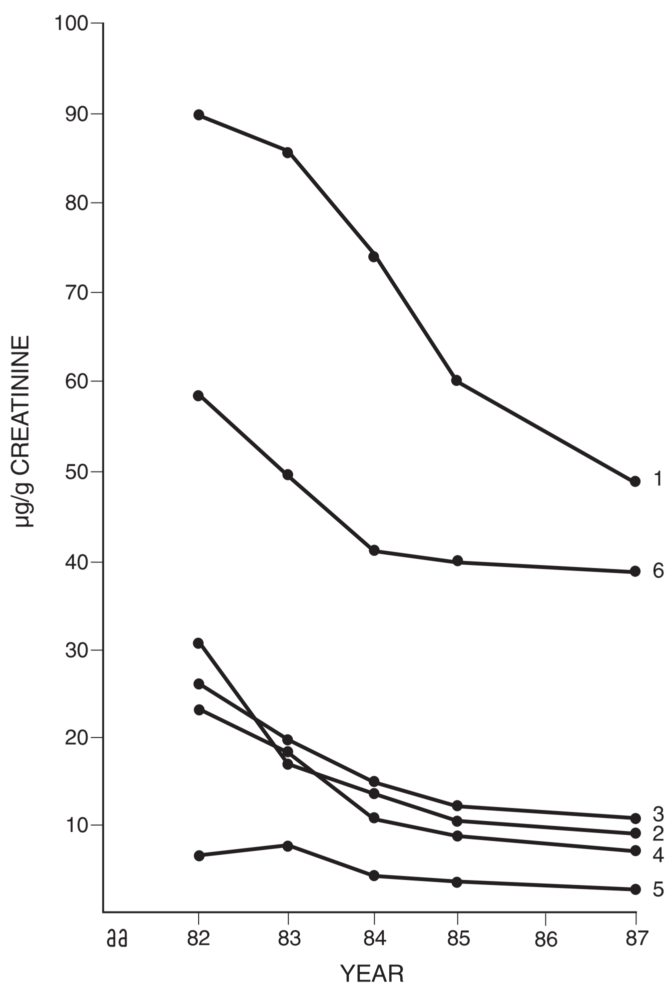

Figure 5B – Cadmium Levels in Urine in Six Welders During the First 5 Years After Exposure to Cadmium Ceased. Trevisan and Maso, Ref. 204

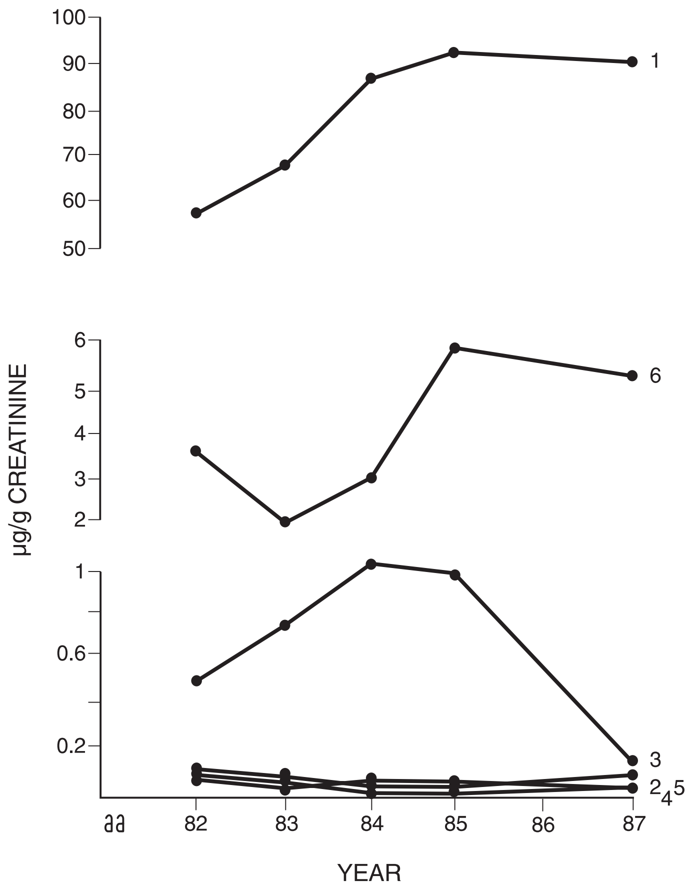

Figure 5C—Concentrations of Beta 2-Microglobin in Urine of Six Welders During the First 5 Years After Exposure to Cadmium Ceased. Trevisan and Maso, Ref. 204

between April 1964 and December 1984. Data on occupational exposures and history, welding method used, and drinking and smoking habits were obtained by a self-administered postal questionnaire in 1986. Birth rates among welders were compared with those of men selected from the Danish Central Population Register.

Among subjects who had ever welded, the probability of fathering a child during years when they were not welding was significantly greater than that of metal-workers who had never welded (OR = 1.27; $p<0.001$). Because of this, the investigators considered it inappropriate to compare fertility of ever welders with those who had never welded. Instead, the analysis was restricted to subjects who had ever welded, and fertility during years at risk from welding was compared with fertility during years with no welding exposure. Among persons who had ever worked as welders, the probability of fathering a child was slightly, but significantly, reduced during the year following a year of welding exposure (OR = 0.89; P = 0.005). The reduction in fertility was associated with the welding of mild steel (OR = 0.86; P = 0.03) but not with SMAW or GTAW of stainless steel (OR = 0.98). The authors concluded that welding mild steel is associated with a slight, but significant decrease in male fertility.

To determine whether these observations correlated with changes in physiological parameters, Bonde (Ref. 33) compared semen quality and serum levels of sex hormones [follicle stimulating hormone (FSH) and luteinizing hormone] among 35 stainless steel (GTAW) welders, 46 mild steel (SMAW and GMAW) welders and 54 non-welding metal workers. The study participants were from six workplaces in Denmark. Mean exposure to fume particulates was 1.3 mg/m^3 for stainless steel welders, and 3.2 and 4.7 mg/m^3 for mild steel welders with "low" and "high" exposures, respectively. These levels were within Danish process-specific threshold limit values for welding.

The sperm count, proportion of normal sperm forms, degree of sperm motility, and the linear penetration rate were significantly decreased in mild steel welders, while there was no significant change in the sperm concentration of FSH. Follicle stimulating hormone concentrations increased with increasing welding exposure and, with the exception of sperm count, semen quality decreased. The effects were less marked in stainless steel welders who had significantly decreased semen volume, total sperm count, proportion of motile sperm, and concentration of serum testosterone.

To determine if the changes in semen quality were reversible, semen quality was examined in 19 of the mild steel welders, 18 of the stainless steel welders and 16 of the non-welding metalworkers before, and 3, 5, and 8 weeks after a 3-week, welding-free vacation period (Ref. 34). Three post-vacation collection time points were included to allow detection of changes that occurred at different stages in sperm development. No significant improvement in any of the semen parameters was observed at any of the post-vacation time periods relative to the pre-vacation values.

While Bonde's studies suggest a reduction in fertility and semen quality with welding, the changes observed were slight, albeit significant. A positive dose-response was not obtained when fertility was considered in terms of years of welding exposure. An increase in effects with increased years of exposure would have strengthened the observations.

Never welders were excluded from the large cohort study (Ref. 35) because their fertility rate was lower than that of welders during periods of nonexposure. The rationale for excluding nonwelders from the study is not clear, and it is possible that a direct comparison between the overall fertility rates among welders (including periods of both welding and nonwelding) and nonwelders would have shown no difference between the two groups.

Bonde's conclusion that welding reduces fertility was based on differences in birthrates between periods of welding and nonwelding in the same cohort. Alternatively, physical or psychological stresses encountered during welding could have decreased interest in fathering a child; the welders could have delayed conception, either consciously or subconsciously, until periods when vocational stresses were reduced. Thus, differences in the fertility of welders between periods of welding and nonwelding may not actually reflect physiological changes brought about by welding exposures. Perhaps a more valid comparison would be between men who were never welders and those who worked continuously as welders during their entire family raising period.

Finally, while the investigation of semen quality supported the concept that welding is associated with decreased fertility, there were some inconsistencies between the findings of the fertility and semen quality studies. These are (1) a reduction in semen quality was observed in stainless steel welders whose fertility rates were not altered in the epidemiologic study and (2) fertility, but not semen quality, improved during a period of nonwelding. As Bonde pointed out, the observed changes were small and thus subject to confounding factors which are impossible to control with human populations. Because the effects are small, controlled studies in laboratory animals may be necessary to resolve questions concerning the effects of welding exposures on fertility.

20. Teeth

Tatintsyan and Abgaryan (Ref. 197) surveyed electric arc welders and determined that 87% have some degree of periodontal disease and gingivitis. To determine whether the problem was related to a lack of defenses against bacterial growth in the mouth, they measured the concentration of lysozyme in saliva collected from each of 35 welders and 28 nonwelding controls. Lysozyme, an enzyme destructive to the cell wall of some bacteria, is a normal constituent of saliva and other body fluids. It was used as a measure of the ability of the body to repress the population of micrococcus lysodenticus in the mouth. Average lysozyme concentrations were 167.5 ± 8 µg/ml in the control population and 103.7 ± 13 µg/ml in welders. These investigators developed a small filtration device to protect the mouth from exposure to welding fumes. After using the device for 2 years, lysozyme increased from 103.7 to 148.5 µg/ml in welders. In addition, use of this device reduced the concentrations of Mn and Zn in saliva.

21. Effects of Specific Metals

21.1 Beryllium. Acute berylliosis, caused by brief exposure to high concentrations of beryllium fumes, is characterized by inflammation of the nasopharynx, trachea, and bronchi, with possible development of pulmonary edema. Chronic berylliosis, caused by long-term exposure to low concentrations of beryllium is typified by a granulomatous process in the lung which may not become apparent until months or years after exposure ceases. Either can be fatal.

A typical case of chronic beryllium disease in a fifty-one-year-old Scottish welder was described by Monie and Roberts (Ref. 138). The welder had a long-standing cough with morning production of mucoid phlegm; his chest x-ray showed reticulonodular shadowing. Examination showed reduced pulmonary function, and biopsies revealed mild fibrosis and epithelioid cell granulomas. The identification of beryllium in biopsied lung tissue, led to the diagnosis of this condition as chronic beryllium disease producing a granulomatous pneumonitis. The electrical firm where he had worked had closed, and it could not be confirmed that he had worked with beryllium. However, the Heath and Safety Executive of Scotland confirmed that the Sciacky process, with which he had worked, used a consumable electrode of a copper alloy containing between 2 and 3% beryllium.

21.2 Cadmium. Acute inhalation of cadmium fumes can cause metal fume fever-like symptoms with fever, headache, shortness of breath, chest pain, abdominal pain, vomiting, diarrhea, irritation of the mucosa, and muscle pain. In addition, cadmium is a severe respiratory irritant and exposure can cause pulmonary edema (accumulation of fluids in the lung) within hours after exposure, followed by chemical pneumonitis.

Yates and Goldman (Ref. 225) described a case of acute cadmium poisoning who had been brazing ship propellers with an oxyacetylene torch using an alloy containing 20% cadmium propellers in a confined space with poor ventilation. Ten days after working in these conditions, he began to experience malaise and breathlessness and developed fever and joint pain. A physical examination revealed widespread inspiratory crackles over both lower lobes, and a chest X-ray showed mottled shadowing in the lungs. Lung function was restricted (FEV_1 and FVC were reduced). With prednisone therapy, his lesions resolved completely within several months.

Fuortes et al. (Ref. 67) described an acute fatality in a man who was using a propane torch and a soldering gun to join sheet metal surfaces in an unventilated garage. After three days of this activity, he developed an extremely high fever, a cough, and abdominal pain. He died three days later in the hospital. Autopsy revealed pulmonary edema and congestion. Exceedingly high cadmium levels (280 ng/ml) were discovered during a heavy metal screen of cardiac blood (allowable occupational blood levels are <5 ng/ml). Milligram quantities of cadmium were identified by AAS on the soldering gun tip and sheet metal samples with which he had been working.

21.3 Iron. Noting that iron constitutes up to 50% of the solid component of welding fumes, Lubianova (Ref. 126) conducted a survey of iron content and transferrin, an iron binding and transport protein, in the blood of welders. Welders were divided into groups as follows: 1) healthy high-alloy steel welders; 2) healthy medium- and low-alloy steel welders; 3) healthy cast iron welders; 4) welders with pneumoconiosis; and 5) welders with chronic bronchitis. Almost half the welders had elevated blood iron levels when compared with nonwelding controls. Welders without pneumoconiosis had less blood iron than welders with pneumoconiosis. The serum of welders had twice the iron-binding capacity of nonwelding controls, due to the increase of transferrin. In all but welders with pneumoconioses, the iron saturation of transferrin was less than controls. The investigators concluded that in welders, the overburden of iron is accommodated by increases in transferrin levels.

22. Biological Monitoring

The quantity of airborne substances to which workers are exposed is determined by measuring breathing zone concentrations of pollutants. Measurement of chemicals in body fluids (e.g., blood, urine, expired air) allows the determination of the amount of a compound that is actually absorbed by the body. Both of these techniques are important for monitoring and controlling occupational and environmental exposures. A third technique, identification of biomarkers, is useful in epidemiologic studies for demonstrating that exposure to specific chemicals has occurred. Biomarkers may detect low levels of exposure but are generally less quantitative than data obtained by biological monitoring. Typical biomarkers are hair concentrations of metals and chemical modifications of DNA or protein in blood or tissues. Both biological monitoring and biomarkers are considered below.

22.1 Chromium: Biomarkers. The toxicity of chromium is related to its valence state. Hexavalent chromium is more toxic than trivalent chromium and some hexavalent, but not trivalent, chromium compounds are mutagenic and carcinogenic. Hexavalent chromium enters cells much more readily than trivalent chromium, which may account for differences in their toxicity. Once in the cell, hexavalent chromium is reduced to the trivalent form which, along with intermediate oxidation states, is thought to be ultimately responsible for chromium carcinogenicity.

Chromium compounds induce DNA lesions which are thought to be related to their mutagenicity and carcinogenicity. *In vitro* and *in vivo* laboratory studies have generally shown that hexavalent chromium, but not trivalent chromium, causes an increase in the frequency of sister chromatid exchanges (SCE). An increased frequency of SCE has also been observed in studies of welding fumes in laboratory animals, and is generally attributed to the hexavalent fraction. However, SCE tests on workers exposed to nickel and chromium have yielded conflicting results.

Using SCE and alkaline filter elution, a test which detects DNA strand breakage, Popp et al. Ref. 165) attempted to resolve this conflict. Urine samples and blood lymphocytes were obtained from 39 electric arc welders and 18 controls. The welders were employed full time, welding low-to medium-alloy steel with electrodes composed of 18% chromium, 8% nickel, and 6% manganese. The average SCE frequency was significantly lower for welders than for the controls. However, with alkaline filter elution, the elution rate through two filter types was lower for DNA from welders than from controls, indicating the presence of DNA-protein cross-links. The frequency of SCE and the extent of DNA-protein cross-linking significantly correlated with urine chromium, but not with urine nickel concentrations. DNA-protein cross-links can reduce the frequency of SCE and the measurable frequency of strand breakage. Thus, performing SCE analysis alone could lead to the false impression that DNA integrity remains intact in chromium-exposed workers. According to the authors, these results confirmed other studies that indicated an important role for DNA-protein cross-links in the mechanism of chromium carcinogenicity.

Coogan et al. (Ref. 50) investigated whether the chromium content of lymphocytes can serve as a biomarker for long-term chromium exposure. The kinetics of chromium uptake in red blood cells has been well studied, but little is known about uptake by lymphocytes. Reasoning that, unlike red blood cells, lymphocytes are long-lived, Coogan maintained that lymphocyte chromium may be a better biomarker for long-term exposure than red blood cell chromium. Isolated rat and human white and red blood cells were exposed to radiolabeled hexavalent chromium in the form of potassium chromate ($K_2{}^{51}CrO_4$) for 2 hours. White blood cells accumulated significantly more chromium than did red blood cells. In other experiments, chromium levels in rat red and white blood cells were determined at 1 hour, 24 hours, and 7 days after oral exposure or intravenous injection. White blood cells consistently accumulated more chromium than did red blood cells. Chromium was undetectable in white blood cells, and present in only low levels in red blood cells, after administration of trivalent chromium (chromic chloride). The chromium content of red blood cells was independent of the valence state of the administered chromium. The investigators concluded that the exclusive accumulation of hexavalent chromium by white blood cells supports their use as target cells in the development of biomarkers for assessing exposure to chromium.

22.2 Chromium: Biological Monitoring. Urinary chromium levels vary positively with air concentrations and, thus, can be used to monitor workplace exposures to chromium fumes (Ref. 190). The kinetics of chromium absorption and excretion have been studied under conditions of relatively high exposures which may not be applicable to monitoring workers who experience low-level long-term exposure to chromium. This area of study is receiving more attention along with investigations of the potential health effects of chronic exposure to low levels of chromium.

Bonde and Christensen (Ref. 36) determined chromium levels in body fluids from welders working with processes that generate fumes containing low concentrations of chromate. Urine, blood, and seminal fluid were collected from 60 welders (30 worked with GTAW of stainless steel, the others worked with SMAW or GMAW of mild steel) and 45 nonwelding controls selected from six plants in Aalborg, Denmark. Ambient air concentrations of welding fume particulates and chromium were within acceptable limits. (Environmental concentrations of particulates, total chromium, and hexavalent chromium levels were 0.94, 0.011, and 0.003 mg/m^3, respectively, among stainless steel welders and 3.1, 0.003, and 0.001 mg/m^3, respectively, among mild steel welders.)

Chromium concentrations were significantly higher in blood and urine from stainless steel and mild steel welders than from controls. However, the concentrations of chromium in blood and urine did not change across a workshift (i.e., there was no significant difference between chromium levels in pre-shift samples collected on Monday morning and post-shift samples collected on Thursday of the same week). Furthermore, urine and blood chromium concentrations did not change after a 3-week vacation break from welding. The authors found these data to be consistent with a gradual buildup of chromium in the body during long-term welding exposure.

High concentrations of chromium were found in seminal fluid obtained from subgroups of welders conducting SMAW of stainless-steel. However, there was an extremely wide variation in chromium levels, which indicated that chromium in seminal fluid may have derived, in part, from nonoccupational activities. Bonde stated that there is a need for further determinations of chromium levels in seminal fluids since some of his other studies (Refs. 32 and 35) suggested a reduction in fertility in welders. In addition, attention should also be focused on the potential risk of delayed health effects among welders who heretofore were not thought to be at risk from chromium exposure.

Biological monitoring of low-level chromium exposures is also being studied by Bukowski et al. (Ref. 41). Because studies in which effects are low and difficult to detect are easily confounded by external factors unrelated to occupational exposures, Bukowski et al. (Ref. 41) focused at first on determining nonvocational factors which could introduce errors into biological monitoring data. The subjects in this ongoing study are state workers in Hudson County, New Jersey who experienced low-level and intermittent exposures to soils heavily contaminated with chromium. The contamination resulted from the use of industrial wastes containing 2–5% hexavalent and trivalent chromium as fill and diking material in state and community parks.

Chromium was determined in urine and blood samples obtained from 52 subjects employed in the community and state parks. Chromium was detected in all but two urine samples. Each subject completed a questionnaire addressing potential confounding variables. Age, educational background, physical fitness, 12-hour fasting, and dietary factors did not elevate either urinary or blood chromium concentrations. Males had slightly higher urinary chromium levels than did females. Beer drinking caused a significant increase in urinary chromium. Subjects who used tobacco, or who had exercised within 24 hours before sampling, had slightly lower chromium levels in the urine. Neither welding nor engaging in hobby activities with possible chromium exposures was associated with increased concentrations of chromium in the urine or blood. Persons with a history of having worked in two or more chromium industries had nonsignificantly higher median urinary chromium concentrations. This study is important because of its general implications for studies of exposure to low levels of chromium.

22.3 Nickel. Angerer and Lehnert (Ref. 5) determined nickel levels in erythrocytes (red blood cells), plasma, and urine from 103 stainless steel welders who worked with chromium-nickel alloyed steel (18% Cr, 10% Ni, 6–8% Mn) at a shipyard in Germany. Thirty-nine welders conducted SMAW, 14 used GMAW only, and 50 used both SMAW and GMAW. The average breathing zone concentration of nickel was 93 $\mu g/m^3$. All values were below the German Technical Guidance Concentration of 500 $\mu g/m^3$. GMAW welders were exposed to somewhat higher nickel levels than SMAW welders. The control population was composed of 123 men and women with no occupational nickel exposure.

Nickel was not detected in erythrocytes from welders or from controls. While nickel was undetectable in control plasma, 82 of 103 welders had measurable plasma nickel. (Average nickel concentration in plasma = 4.9 µg/L) Nickel concentrations in control urine ranged from <0.1 to 13.3 µg/L and were below 2.2 µg/L in 95% of the controls. Nickel levels were considerably higher in the urine of welders, with the average concentration being 18.5 µg/L. Only a weak correlation was noted between nickel levels in plasma and urine in welders. The authors calculated that urinary nickel levels between 30 and 50 µg/L would correspond to an air exposure of 500 $\mu g/m^3$.

22.4 Aluminum. In a study of 23 Swedish welders published in 1988 (Ref. 187), Sjogren, Elinder et al. found that the aluminum content of urine increased with the duration of the welding experience. This suggested that retained aluminum has a long biological half life. Aluminum excretion by two workers from that study was further examined in later work by this group (Ref. 59). Because of the possibility that aluminum may be stored in bone, aluminum concentrations in bone biopsies were also examined in these two volunteers. Both workers had conducted GMAW for at least 20 years prior to 1984. In 1984, worker "B" switched from GMAW to GTAW and worker "A" became a foreman. As a result of these changes, the aluminum exposure of these two men was considerably reduced. Aluminum concentrations in their urine was measured four times between 1984 and 1989 (Figure 6). Urinary aluminum excretion remained high for the 5-year period after exposure decreased. In 1989, the aluminum concentrations were still more than

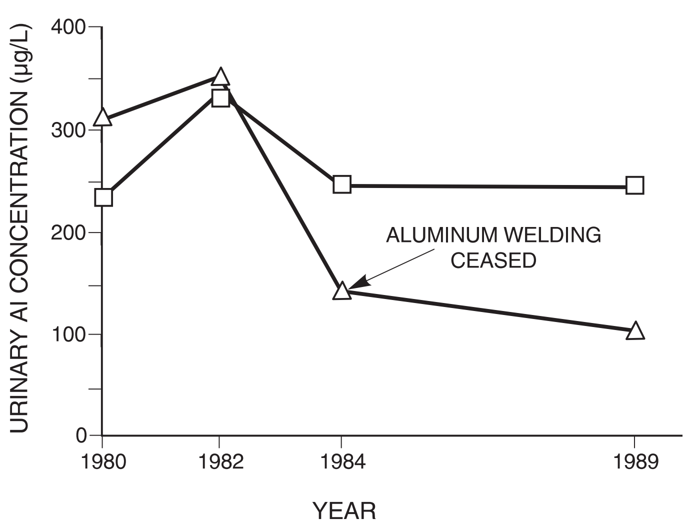

Figure 6—Aluminum Concentrations in Urine from Two Welders During the First 4 Years After Welding of Aluminum Ceased. Elinder et al., Ref. 59

10 times the concentration found in persons without occupational exposure (<10 µg Al/L). The aluminum concentrations in bone were 18 and 29 µg/g for workers A and B, respectively, compared to normal levels in unexposed controls of 0.6 to 5 µg/g. Exposures to total fumes were measured in 1982 and averaged 8.9 and 3.0 mg/m^3 for workers A and B, respectively. No further exposure measurements were taken after 1984, so the reduction in exposure was not documented. The investigators concluded that aluminum accumulates in the skeleton and tissues following long-term inhalation exposure and that the elimination of retained aluminum is very slow, on the order of several years.

22.5 Zinc. Chughtai et al. (Ref. 49) surveyed zinc concentrations in blood from a sample of welders and nonwelders residing in the city of Hyderabad (Sindh). Zinc concentrations were significantly higher in serum from electric arc and gas welders than from controls.

23. Incidental Exposures

Welders occasionally experience respiratory distress, immune reactions, or other toxic effects from exposures to chemicals incidental to the welding process. Exposures in this category include chemicals thought to be generated by photochemical decomposition products of degreasing agents and pollutants generated by pyrolysis or thermal degradation of paints or other surface coatings or contaminants. These exposures are not inherent to welding and, with little exception, they can be avoided by changes in the manufacturing process and use of proper ventilation and safety techniques.

23.1 Degreasing Agents. Degreasing agents can present a major hazard in welding. Severe acute respiratory distress can result from such highly toxic chemicals as phosgene and dichloroacetyl chloride, that can arise from UV-induced photochemical decomposition of degreasing agents such as trichloroethylene, perchloroethylene and 1,1,1-trichloroethane. This type of hazard is greatest in shops where GMAW or GTAW is conducted since these processes can produce high levels of UV radiation. While, in the past, several incidents of severe respiratory distress were thought to have resulted from the photochemical decomposition of degreasing agents, the actual presence of phosgene and/or dichloroacetyl chloride has been hard to substantiate.

In 1991, Sjogren (Ref. 191) reported an incident in which a 50-year-old, highly experienced welder performed GTAW on a piece of stainless steel that had been degreased with trichloroethylene. The welding was done without local exhaust ventilation to avoid disturbing the gas shield. Almost immediately after starting to weld, he developed dyspnea. He rested, recovered, and returned to welding with no further symptoms until 12 hours later, when he developed severe respiratory distress and pulmonary edema. He was treated for these symptoms but was readmitted to the hospital 10 days later with dyspnea and respiratory failure. His exposure to trichlorethylene was confirmed by the presence of trichloroacetic acid (a metabolite of trichlorethylene) in his urine. Sjogren et al. speculated that the severe pulmonary reactions might have been due to inhalation of the photochemical decomposition products dichloroacetyl chloride and phosgene. However, no attempt was made to determine whether phosgene or dichloroacetyl chloride could form under welding conditions similar to those experienced by the affected welder.

In a similar case involving 1,1,1-trichloroethane (methylchloroform) exposure, Selden and Sundell (Ref. 181) “extensively investigated the phosgene theory but with a frustrating outcome, illustrating the inherent problems of retrospective exposure assessment.” In this case, a 62-year-old man had been welding mild steel items covered with a drawing oil using GMAW with an argon/carbon dioxide gas shield. 1,1,1-Trichloroethane stabilized with dioxane was used to degrease the pieces before welding. After welding under these conditions for 3 days, he developed fever and severe respiratory distress and eventually died. No phosgene was detected during a reconstruction of this incident at the worksite, even in the presence of inordinately high levels of 1,1,1-trichloroethane (740 ppm). Phosgene could only be detected when the concentration of airborne 1,1,1-trichloroethane reached 1000 ppm during welding. The investigators concluded that, while the presence of phosgene could not be confirmed, the illness, diagnosed as toxic pulmonary edema, was related to welding in the presence of a chlorinated solvent.

23.2 Coated or Contaminated Surfaces. Two experienced welders who developed fever, spirometric deterioration, and bronchial hyperreactivity after GMAW of steel painted with lacquers containing chlorinated polymers were described by Sjogren et al. (Refs. 185 and 8) Backstrom et al, 1991). The first welder, a 54-year-old Swedish male, experienced eye and throat irritation and shortness of breath shortly after his first experience welding steel coated with a new paint (Beckrysol Grundfarg-BF paint). He developed a high fever later that evening. The same symptoms occurred on six other occasions when he welded steel coated with this paint. Repeated spirometric testing showed volume and flow decrements that slowly returned to normal. The second man, a 49-year-old Swedish welder, developed fever and shortness of breath 5 to 6 hours after welding steel that had been coated with a paint (Realux Grund paint) similar in composition to the Beckrysol Grundfarg-BF paint used by the first welder. He felt tired for several weeks thereafter. He experienced similar symptoms on four other occasions when he welded steel coated with the same paint, although the symptoms were milder and of shorter duration. Repeated spirometric measurements showed flow and volume decrements that slowly normalized.

Both welders were exposed to compounds generated by pyrolysis of paints which were epoxidized vegetable oils hardened by hexachloroendomethylene-tetrahydrophthalic acid anhydride (HETacid anhydride). Limited tests demonstrated that HCl, but not phosgene, is released from this paint during welding. The authors concluded that the two welders had toxic alveolitis and obstructive lung disease induced by HCl and other chlorinated compounds. They related the symptoms to reactive airways dysfunction syndrome (RADS), which is characterized by asthma and bronchial hyperreactivity and develops after one or more exposures to high concentrations of low-molecular weight respiratory tract irritants. Symptoms of RADS may be aggravated by nonspecific irritants. They speculated that HETacid anhydride may have been one of the components responsible for this syndrome.

A similar case in which prolonged respiratory symptoms resulted from welding exposures was described by Langley (Ref. 119). The 29-year-old male patient had worked as a welder for 10 years. On one occasion, he was brazing a piece of galvanized steel and a brass pipe fitting using a 15% silver alloy brazing rod. Teflon™ tape covered the connection near where he was brazing. He was not wearing a respirator and was brazing in an unventilated room with the windows and doors closed. Within twenty minutes, he developed shortness of breath, coughing, sweating, back pain, headache and a sweet metallic taste in the mouth. Chest X-rays showed signs of mild pulmonary edema. Two days later, shortness of breath continued, and wheezing was present along with increased levels of SGOT and SGPT, serum enzymes indicative of liver injury. Breathing and pulmonary function improved over several months. His persistent wheezing, exacerbated by some odors and tobacco smoke, also gradually decreased in severity. The wheezing had apparently diminished noticeably on the last examination and the patient was lost to follow-up thereafter. The authors diagnosed this illness as RADS associated with welding exposures. While this syndrome is known to occur after exposure to certain irritant chemicals, it has not been associated with welding *per se*, and, in this case, it may have been due to an incidental exposure to pyrolysis of the Teflon™ tape or to other coatings or contaminants on the pieces being brazed.

Lipoid pneumonia results from chronic inhalation or aspiration of mineral oil mists and has only rarely been associated with occupational exposures. Symptoms of diffuse, interstitial lipoid pneumonia can range from occasional cough to severe, debilitating dyspnea, fibrosis, and loss of pulmonary function; it is occasionally fatal (Ref. 159). Penes et al. (Ref. 162) described a welder who developed diffuse, interstitial lipoid pneumonia attributed to exposure to mineral oil during welding. This 45-year-old patient had been exposed to oil spray for 16 years, and described his work as welding pieces of steel covered with cutting oil. Bronchoalveolar lavage fluid and pleural fluid were obtained from the patient, extracted with hexane, and analyzed by GC/MS. The compounds identified in these analyses were virtually identical to those found in extracts from cutting and stripping oils, leading to the conclusion that exposure to cutting oils was the probable cause of his lung disease.

23.3 Allergens. Blomqvist et al. (Ref. 128) reported a case involving a 33-year-old male welder who developed bronchial asthma following exposure to chloramine-T, a strong oxidizing compound with antiviral, bactericidal, and fungicidal properties. A few minutes after welding a container that was used for storing chloramine-T powder, he developed rhinitis. Six months later, he was repairing an industrial vacuum cleaner containing chloramine-T when he experienced severe shortness of breath and wheezing in the chest. Skin prick tests showed a positive reaction to chloramine-T.

Kanerva et al. (Ref. 107) reported the case of a welder who, on four separate occasions, developed an urticarial reaction associated with high fever and facial edema while welding mild steel profiles filled with polyurethane. Urticaria is an itchy skin rash which develops in sensitive persons after exposure to particular drugs or chemicals. The symptoms resolved within 48 hours. The welder was tested for sensitivity to chemicals such as 4,4-diphenylmethane diisocyanate and 4,4-diaminophenylmethane, which could have been emitted during the welding of polyurethane. These tests were negative and the chemical(s) to which he was sensitized remain(s) unknown.

Section Three Investigations in Animals and Cell Cultures

25. Fertility

Ernst (Ref. 63) examined the effects of trivalent and hexavalent chromium on the reproductive system in male Wistar rats. The animals received daily intraperitoneal injections of chromium chloride [Cr(III)] or sodium chromate [Cr(VI)] for 5 consecutive days. There were no testicular changes 7 days after the last exposure. However, after 60 days, hexavalent chromium caused a reduction in testicular weight and a dose-dependent increase in the number of atrophic seminiferous tubules. Sixty days after administration of the highest dose tested (4 mg/kg body weight), almost all of the seminiferous tubules were completely degenerated and there was a marked reduction in the epididymal sperm count (Table 3). None of these effects were seen with trivalent chromium. The investigators suggested that the differences in toxicity between the two valence states was related to the more ready absorption and cell penetration of hexavalent chromium.

Table 3
Effect of Short-Term Exposure to Tri- and Hexavalent Chromium on Testicular Weight, and Number of Spermatozoa per Epididymis in Adult Wistar Rats

Treatment	Body Weight (g)	Relative Testicular Weight[a] (g/100 g)	Spermatozoa/ Epididymis ($\times 10^6$)
Control	448.8±7.7	1.06±0.04	640±11
Cr(III) 1 mg/kg	419.4±11.6	1.03±0.04	630±12
Cr(III) 2 mg/kg	457.0±8.0	1.05±0.04	634±11
Cr(III) 4 mg/kg	429.8±7.3	1.04±0.03	629±9
Cr(VI) 1 mg/kg	442.0±9.3[b]	1.71±0.05[b]	369±12[b]
Cr(VI) 2 mg/kg	367.1±12.7[b]	1.69±0.05[b]	131±5[b]
Cr(VI) 4 mg/kg	390.9±10.9[b]	1.58±0.04[b]	49±7[b]

[a]Testicular weight (g)/body weight (g)
[b]Statistically different than control animals ($p<0.01$)
Data from Ernst, Ref. 63

Hicks and Olufsen (Ref. 89) investigated whether myofibroblasts proliferate in fibrotic processes in lungs exposed to welding fumes. Rats were exposed by intratracheal instillation to crystalline silica or to particles from fumes generated by GTAW of mild steel. The animals were sacrificed, and strips of lungs were removed and placed in tissue culture medium. Contractility, indicative of myofibroblast activity, could be stimulated in fibrotic tissues from rats treated with either silica or welding fumes. Histological examination confirmed the presence of myofibroblasts in fibrotic lung tissue.

26. Fibrosis

Collagen, the most abundant protein the body, forms insoluble fibers which provide the mechanical and supportive functions of connective tissues. At least four unique collagens (Types I through IV) are found in the body. They differ somewhat in amino acid composition and are found in specific tissues. When more than one type of collagen is found in a tissue, the proportions of the different types are characteristic and constant. A major characteristic of lung fibrosis is a massive increase in interstitial collagen. Lung tissue normally contains Types I and III collagen. In a study of the process of lung fibrosis, Yurui and Yu (Ref. 228) investigated whether the proportions of the two types of collagen in the lung change during the fibrotic process. They further examined whether welding fumes, which are mildly fibrogenic, and quartz, a highly fibrogenic material, produce the same changes in collagen during fibrosis.

An enzyme-linked immunosorbent assay (ELISA) was used to determine the content and distribution of Type I and Type III collagen in female Wistar rats exposed by intratracheal instillation to either quartz dust or welding fume. (Details about the welding process used to generate the fumes were not given). With welding fumes, the content of Type III collagen in the lung was significantly greater 30 days after exposure but Type I collagen did not increase until about 180 days after exposure. Because of this, the ratio of Type I/Type III collagen decreased gradually for about 180 days before it began to return to normal levels. In contrast, instillation of quartz caused a continuous increase in both Type I and Type III collagen. These results suggest that different mechanisms are involved in the cellular response to highly fibrotic and mildly fibrotic dusts. The authors concluded that the ratio of Type I to Type III collagen can be used for evaluation of the fibrogenicity of respirable dusts.

27. In Vitro Tests

Ozone, a strong respiratory tract irritant, is produced in substantial amounts during hyperbaric inert gas welding. Ozone is known to reduce the phagocytic activity of alveolar macrophages. In continuing studies of the effects of hyperbaric pressure on physiological functions, Jakobsen et al. (Ref. 101) found that the phagocytic activity of rat alveolar macrophages is not affected by elevated pressure. However, the combined effects of pressure and ozone caused a greater reduction in phagocytic activity than did ozone alone, indicating that increasing pressure may increase the effects of ozone on alveolar macrophages.

Polymorphonuclear leukocytes migrate into the lungs and other tissues in response to the presence of foreign materials. They play a major role in the inflammatory process and are important in defending the body against bacteria. When PMNs interact with fibrogenic materials, they release superoxide which is converted by the enzyme superoxide dismutase to hydrogen peroxide. The PMN enzyme myeloperoxidase can further convert the hydrogen peroxide to hypochlorous acid (HOCl). These strong oxidants contribute to the destruction of invading bacteria, but they can also damage lung tissue. The generation of oxidants by PMNs can be assayed with the chemiluminescent compound luminol. Upon reaction with oxidants, luminol generates a flash of light which is readily detected with a liquid scintillation counter. This reaction forms the basis for the chemiluminescence assay, a widely used immunological test.

Saburova et al. (Ref. 177) used the chemiluminescence assay to determine whether welding fumes and other fibrogenic dusts elicit the formation of HOCl by isolated PMNs. While human PMNs generated HOCl in response to opsonized zymosan (a complex carbohydrate obtained from the walls of yeast cells), none of the three fibrogenic dusts tested (quartz, natural zeolite, and welding fumes) stimulated HOCl formation. The authors concluded that HOCl does not play a role in the pathogenic processes associated with inhaled welding fumes.

Adamis et al. (Ref. 1) compared the biological activity of fumes collected from GTAW of an aluminum-magnesium alloy with dusts collected from other operations in an aluminum plant in Hungary. Red blood cell hemolysis, interference with macrophage metabolism, as indicated by a decrease in the reduction of the dye triphenyltetrasolium chloride, and lysis of macrophages, as indicated by the release of the enzyme lactic dehydrogenase into the culture medium, were determined. None of the three samples was classified as hazardous on the basis of the experimental results. However, welding fume particulates were more toxic than the other dust samples collected.

28. Effects of Welding Fumes in Animals

Naslund et al. (Ref. 143) examined pulmonary effects in sheep of welding fume produced by SMAW of black iron. In the first experiment, a single dose of 0.5 gram SMAW fume particulate was administered to sheep by intratracheal instillation. Acute exposure to welding fume significantly increased the mean pulmonary arterial pressure and the number of alveolar leukocytes. Hematocrit values, arterial oxygen tension and pO_2 were reduced. The sheep were killed 4 hours after exposure and the lungs removed and analyzed for metal content. Fe, Mg, Ti, Al, and Mn accumulated in the lungs. Mn levels were increased 40-fold over control values.

In a second study, designed in part to examine the distribution of welding fume in the body, sheep were tracheotomized and exposed by inhalation to welding fumes 3 hours a day, 5 days a week for 25 to 33 weeks. Iron oxide accumulation was monitored by magnetopneumography. Sheep were killed after the last exposure and the lungs were removed and examined for histopathological changes. Fibrosing pneumonitis and slight emphysema were observed in lung tissue. The concentrations of Cu, Ti, Mg and Zn were determined in skeleton, kidney, lung and liver. None of the metals was elevated in bone or liver. The concentrations of Mg and Mn were slightly increased in the kidney. Substantial amounts of Mn and iron accumulated in the lungs. None of the metal concentrations in the blood or lymph was significantly altered by exposure.

Pokrovskaia and Cherednichenko (Ref. 163) compared the effects of fumes from five different welding electrodes on the cardiovascular system and respiratory tract in rats. Fumes (12.5 mg/kg per dose) were administered by intratracheal instillation once weekly for 4 weeks. The proportions of five elements among the different fumes were: Mn (7.5 to 11%), Si (1.9 to 18.9%), K (3.5 to 27.1%), Na (5.0 to 15.3%), Ca (1.4 to 22.0%), F (9.6 to 20.0%), and Fe (18.0 to 29.9%); details on the composition of the individual welding fumes were not given. Rats were sacrificed at 1, 3 and 6 months after treatment, and tissues were examined by histopathological techniques. After 1 month, swelling of the bronchial epithelium, atelectasis (poor expansion of the alveoli), and thickening of alveolar walls were seen in the lungs. Many particles were engulfed by alveolar macrophages. Damaged muscle fibers were seen in the heart. At 3 months, there were still substantial effects in the lung and cardiovascular system. By 6 months, much of the tissue damage had resolved. Fibrosis was not observed at any time. The investigators concluded that toxicity was related to the content of K, F, and soluble Mn compounds in the fumes.

29. Biochemical Studies

In 1987, Geleskul et al. (Ref. 70) described an animal model for testing particle-induced lipid peroxidation. Using this model, they demonstrated that lipid peroxidation can be used as a measure of the toxicity of welding fumes from covered electrodes. More recently, these investigators published a series of papers in which the toxicity of fumes from three different electrodes was measured by lipid peroxidation in the liver and lung (Refs. 71, 72, and 73). The concentrations of Mn, Si and Fe in fumes generated by SMAW with the three electrodes are shown in Table 4. Fume samples (50 mg each) from three different electrodes were administered to rats by intratracheal instillation, and malondialdehyde was determined in lung tissue or liver mitochondria. Fumes from all three electrodes stimulated the formation of peroxides. Peroxidation was greatest in lung tissue at 1 day after treatment and in liver tissue at 7 days after treatment. Fumes from electrode 3 caused more peroxidation in the lungs than in the liver, while fumes from electrode 1 were more active in the liver, and those from electrode 2 were equally active in both organs. The authors deduced from the composition of the welding fumes (Table 5) that manganese is responsible for the liver toxicity and silicon is responsible for lung toxicity. They also found that fumes from electrode 2 caused more lipid peroxidation in the lung than did those from electrode 3 and related this to the greater solubility of fumes from electrode 2. These simplified interpretations of the data do not account for interactions between fume components, or the effects of trace metals or nonmetallic components in the welding fumes.

In a related report, Geleskul et al. (Ref. 74), measured the tendency for welding fumes to cause lipid oxidation in liver mitochondria by determining the effects on the glutathione/glutathione reductase antioxidant system. Fumes generated by welding with two different electrodes were studied. Fumes from the first electrode were high in Ca, K, and F while those from the second electrode had a high concentration of Mn and Na. Welding fumes were administered to rats by intratracheal instillation (50 mg per rat), and the levels of glutathione peroxidase and glutathione reductase (enzymes which regulate the levels of the antioxidant glutathione) were measured in liver mitochondria at 1 and 4 months after exposure. Fumes from both electrodes increased the levels of glutathione peroxidase and glutathione reductase and decreased the content of sulfhydryl groups and glutathione. These effects were strongest with fumes from electrode 1, which the investigators contributed to their greater solubility.

Velichkovskii et al. (Ref. 214) compared the toxicity of fumes from four types of electrodes in three different assays. The first assay measured the effects of the fumes on the chemiluminescence assay with peritoneal macrophages. The second assay examined the potential for producing hemolysis of red blood cells. The third assay measured the potential of welding fumes to cause peroxidation of lipids in the lung. For this assay, welding fumes were administered to animals by intratracheal instillation, and lungs were collected at 1, 7, and 15 days after treatment. Lipid peroxidation was measured by determining the content of malondialdehyde in the lungs.

Table 4
Metal Content of Fumes from Electrodes Tested in Lipid Peroxidation Assays

Fume Sample	Metal Content in Fume			Relative Toxicity	
	Mn	Si	Fe	Lung	Liver
1	16.3	2.0	44.4	–	+
2	18.3	17.4	24.5	+	+
3	3.6	17.5	48.8	+	–

Data from Geleskul et al., Refs. 71, 72, and 73

Fumes from electrodes numbered 2 and 4 were substantially more toxic than those from the other two electrodes in all three assays. The investigators concluded that there is a strong correlation between the toxic activity of the welding fumes in *in vitro* assays and in tests performed *in vivo*. In addition, because the silicon content was highest in the fumes from electrodes 2 and 4, while the manganese and iron content did not correlate with toxicity, they concluded that the toxicity was related to the silicon. As discussed above, these assumptions are greatly simplified, in part because they ignore the effects of trace elements. Only the concentrations of five elements in the welding fumes were determined, and it is possible that trace elements were responsible for the toxicity.

Using the lipid peroxide techniques described by Geleskul et al., (Ref. 70), Kuchuk et al. (Ref. 117) measured malondialdehyde formation in liver tissue from rats treated by intratracheal instillation with fumes from six different electrodes. Chemiluminescence in white blood cells isolated from these animals was also measured. The experimental conditions and the chemical compositions of the fumes were the same as those described in the study by Pokrovskaia and Cherednichenko (1990). Kuchuk et al. concluded that the biological activity is determined primarily by the Mn and Fe content but that it also increases with the concentration of other ingredients as follows (in decreasing order): K, Si, F, Na/Ca. These conclusions are contrary to those of Velichkovskii, (1990) who found no correlation between toxicity and Mn or Fe content of welding fumes.

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