Effects of Welding on Health, I

American Welding Society

Effects of Welding on Health

A literature survey and evaluation to establish the state-of-the-art and to point the directions for future research to understand and improve the occupational health of welding personnel

Research performed at the Franklin Research Center under contract with the American Welding Society and supported by industry contributions

Prepared for:

SAFETY AND HEALTH COMMITTEE
AMERICAN WELDING SOCIETY
550 N.W. LeJeune Road, Miami, Florida 33126

Library of Congress Number: 79-52672
International Standard Book Number: 0-87171-180-X

American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126

Note: By publication of this specification the American Welding Society does not insure anyone utilizing the specification against liability arising from the use of such specification. A publication of a specification by the American Welding Society does not carry with it any right to make, use, or sell any patented items. Each prospective user should make an independent investigation.

Printed in the United States of America

Contents

Personnel

Authors of the report by Franklin Research Center were:

Jon E. Villaume
Khizar Wasti
Deborah Liss-Suter
Shu-hsi Hsiao

AWS Research Committee

J.F. Hinrichs, Chairman	A.O. Smith Corporation
F.Y. Speight, Secretary	American Welding Society
R.E. Kinser	Caterpillar Tractor Co.
P. Ramsey	A.O. Smith Corporation
P.C. Krueger	Airco Welding Products
A. Lesnewich	Airco Welding Products
N. Ward	Caterpillar Tractor Co.

AWS Research Finance Committee

E.B. Scripture, Chairman	Teledyne McKay
F.Y. Speight, Secretary	American Welding Society
W.B. Howell	Consultant
R.E. Bruggeman	Caterpillar Tractor Co.
R.H. Schwegman	General Electric Co.
E.H. Hunt	Allegheny Ludlum Industries

Acknowledgments

The American Welding Society gratefully acknowledges the time and effort expended by the members of the Research Committee and the Research Finance Committee and the financial support of the program by industry contributions.

Supporting Organizations

Alloy Rods
Division of Allegheny Ludlum Steel Company
Westinghouse Electric Company
Airco, Inc.
Miller Electric Company
The Heil Company
United States Steel Corporation
Union Carbide Corporation
Babcock and Wilcox Company
General Electric Company
E.I. DuPont de Nemours & Company
Teledyne McKay, Inc.
J.I. Case Company
Lincoln Electric Company
Huntington Alloys, Inc.
Stoody Company
AWS Detroit Section
Duke Power Company
Sandvik, Inc.

In addition, 21 other organizations made contributions to help support the program during the period January 1978 – April 1, 1979.

Preface

This literature review has been prepared for the Safety and Health Committee of the American Welding Society to provide an assessment of current knowledge of the effects of welding on health, as well as to aid in the formulation of a research program in this area, as part of an ongoing program sponsored by the Committee. Previous work has included studies of fumes and gases, radiation, and noise generated during various forms of arc welding. Conclusions based on this review and recommendations for further research are presented in the introductory portions of the report. Appendix A of this report reviews AWS sponsored studies and others in order to clarify the occupational exposures that are summarized in Chapter 1. Chapters 2 and 3 contain information related to the effects of exposure to byproducts of welding operations on humans and on laboratory animals. Chapter 4 covers studies of the mutagenicity of welding fume condensate.

Introduction

According to census figures (Ref. 1), there were an estimated 572,000 welders and cutters in 1970. Sosnin (Ref. 2) has estimated that today there are close to one million individuals whose occupation requires a substantial amount of welding; this latter estimate includes pipefitters and mechanics who view welding only as one of the tools of their trade. Therefore, the health and safety of this large occupational group is an important concern.

Welders are not a homogeneous group. They work under a variety of conditions: outdoors, indoors in open as well as confined spaces, underwater, and above ground on construction sites. They also utilize a large number of welding and cutting processes. However, many of these have in common the production of fumes, gases, radiation, and other potentially harmful agents. The review that follows attempts to assess the effects of these agents on the health of welders.

The discussion concentrates on health effects due directly to the welding process. It does not attempt to treat safety problems, nor does it cover in any detail the accompanying hazards that, although often found in the welding environment, are not created directly by the welding process.

Occupational health depends upon the conditions and exposures received in the workers' environment. In Chapter 1 of this report, the physical and chemical agents to which welders may be exposed and the conditions of their generation are summarized; details are provided in Appendix A. In Chapter 2, the effects of this exposure on welders and others in the environment are reviewed. Since welders are exposed to a number of factors simultaneously, the chapter is subdivided by organ system, not by agent. Effects on the respiratory system, skin, eyes, and internal organs are considered. Chapter 3 presents the results of studies in experimental animals; the review concludes with a discussion of special studies of the mutagenicity of welding fumes.

Executive Summary

Most commonly used welding processes emit fumes, gases, electromagnetic radiation, and noise as byproducts of their operation. During welding, workers are potentially exposed to all of these agents. The fumes are chemically very complex, arising primarily from the filler metals and any electrode coatings or cores. The potential exposure varies with the process and welding conditions employed.

Numerous reports of the effects of welding on health have been published. Many cases of acute poisoning, due to excess exposure to one or more gases and fumes, have been documented. However, other than lung involvement, few chronic effects have been attributed to welding, and, in almost all the studies of chronic effects, welding of ferrous metals was involved. This does not necessarily mean that welding ferrous or any other metals presents no routine health risks. Frequently, published studies have not been appropriately designed to detect the effects of chronic exposure and have not adequately examined special groups (for example, welders of aluminum or stainless steel) with unique exposure factors. Conclusions resulting from this review are presented briefly in the following sections.

Acute Poisoning

Exposure to ozone generated during gas shielded arc welding, especially of aluminum, may produce irritation and inflammation of the respiratory tract, excess fluid and hemorrhage in the lungs, and sometimes headache, lethargy, and eye irritation. Severe cases could be fatal. Ozone is generated at a distance from the arc by the action of the emitted ultraviolet radiation (<240 nm) on atmospheric oxygen. Nitrogen oxides, which are produced in welding arcs and flames by thermal oxidation of atmospheric nitrogen, produce similar respiratory tract effects.

Metal fume fever occurs in welders who inhale zinc-containing fumes, although other fume components may also produce the symptoms of this condition; for example, a metallic taste, chills, thirst, fever, muscle aches, chest soreness, fatigue, gastrointestinal pain, headache, nausea, and vomiting. The symptoms usually subside within 1 to 3 days of exposure without residual effect.

Chronic Lung Conditions

Protracted inhalation of welding fume particles leads to their accumulation in the lungs, a condition seen as dense areas on chest x-ray films. The severity of changes in lung x-rays is proportional to the length of welding experience; however, the changes seen in such x-rays are not necessarily associated with reduced lung function or disease.

In general, welders of ferrous materials have been found to have an increased frequency of respiratory symptoms such as chronic bronchitis. No conclusive studies have been made to determine whether reduced lung function, emphysema, or other chronic respiratory conditions generally occur more frequently in these groups than in nonwelders.

Significant levels of ozone are produced in certain gas shielded welding operations. Lengthy exposure of experimental animals to this gas has induced the formation of fibrous tissue and caused emphysema-like and other effects in the lungs. No studies of the long-term effects of this gas on welding populations exposed to it have been undertaken.

Studies of the effects of welding fumes on experimental animals have indicated excess deposition of fibrous tissue in the lungs when a variety of metals were welded. However, in these experiments, fume concentrations were always very high, and experimental conditions were incompletely described; therefore, it is difficult to relate the importance of these findings to the welding experience.

Eye

Ultraviolet (>170 nm), visible, and infrared radiation are emitted by the welding arc. Welders not wearing eye protection and others in the vicinity of the arc are at risk to the effects of this radiation.

Ultraviolet radiation produces the condition known as "arc eye," an acute inflammation of the external structures of the eye; the symptoms disappear within 1 to 2 days. Infrared radiation penetrates the interior of the eye and can cause burns on the retina.

There is no evidence that cataracts occur more frequently in arc welders than in nonwelders; the results of studies designed to detect cataracts in welders have yet to be published.

Skin

Exposed skin is susceptible to the effects of ultraviolet radiation from the arc (for example, erythema) and of any fume components capable of skin sensitization or irritation. Chromium compounds, which occur in stainless steel welding fumes, are a frequent cause of dermatitis.

Cardiovascular Disease

Electrocardiograms and blood pressures have been measured in several studies. In most of these, electrocardiograms of welders did not differ significantly from control groups of nonwelders, and welders have been shown to have normal or slightly lower blood pressure than the control groups.

Carbon monoxide is generated from carbon dioxide in the gas shielded welding processes. It combines avidly with hemoglobin, reducing the oxygen-carrying capacity of the blood. Exposure to carbon monoxide may present an added health risk to those with heart disease. No studies of heart disease in welders performing carbon dioxide shielded welding have been documented.

Nervous System and Other Organs

Lead and manganese can occur in the fumes of certain welding operations; both are toxic to the nervous system. Except for those attributable to these two substances, no reliable reports of effects of welding exposure to the nervous system have been published.

There is no significant evidence that welders have a higher incidence of other chronic diseases.

Carcinogenicity

Based upon available information, there does not appear to be any evidence that exposure to welding fumes and gases induces lung or other forms of cancer. Further study is required of groups exposed to specific kinds of fumes. The welding arc emits ultraviolet radiation of wavelengths that produce skin tumors in animals, but no study of this effect in welders has been reported.

Technical Summary

The welding exposure is unique. There is no material from any other source directly comparable to the composition and structure of welding fumes. Exposure to byproduct gases accompanies fume exposure; therefore, ability to extrapolate from exposures received by workers in other industries to those in the welding environment is limited.

Welders are potentially exposed to a large number of chemical and physical agents. Several questions of the effects of welding on health are apparent:

1. Do welders have a higher incidence of chronic respiratory tract disease than nonwelders?
2. Do they have a higher incidence of respiratory tract cancer or other malignancies?
3. Does the ingestion and inhalation of welding fumes and gases result in any other systemic diseases?

Since many different materials and processes are used, these questions should be asked for specific subgroups of welders. In available studies, adequate data to make these distinctions often have not been reported, and any conclusions made apply to welding in general. However, it should be noted that most welding involves ferrous-based metals.

Chronic Respiratory Disease

Protracted inhalation of welding fume particles leads to their accumulation in the lungs. Deposits of these fume particles in the lungs have been noted as dense areas on chest x-ray films. The severity of the changes in the x-rays has been shown to be proportional to the duration of welding exposure (Refs. 3, 4, and 5). However, this evidence of siderosis and pneumoconiosis is not necessarily associated with clinical evidence of lung disease.

Ten major epidemiological studies have contributed to the assessment of risk of chronic restrictive or obstructive lung disease or both in welders. All studies attempted to correct for the confounding effects of smoking. Most obtained previous occupational or medical histories or both (Refs. 3, and 6 through 15). However, in a number of studies (Refs. 3, 8, 9, 11 through 14, 16, and 17), the subjects were shipyard welders in whom concomitant exposure to asbestos is likely; in only one case (Ref. 8) was an attempt made to correct for this confounding effect. Although SMAW or FCAW or both were used by welders in all of the subject populations, descriptive details of the exposure varied between studies and were generally inadequate. All studies were published during 1964 or later except for one (Ref. 3) published in 1947; the latter may not be applicable to current conditions.

The most important criticism of all of these studies is that they were of the "point prevalence" or "cross-sectional" type. In this design, workers at a plant or plants at a particular point in time are studied. Serious bias may enter, because workers who are ill, have died, or have taken up other employment for health-related reasons are omitted. Point prevalence studies are likely to detect only subclinical disease.

Of nine studies that investigated respiratory symptoms, seven (Refs. 3, 7, 9, 11, and 15 through 17) reported an increased prevalence in welders compared to a reference group; in two (Refs. 6, 10, and 12 through 14), no significant difference was found. In only two (Refs. 9 and 16) could a pulmonary function deficit be reasonably attributed to the welding experience; this deficit was stated to be subclinical in one study (Ref. 9) and was probably subclinical in the second. Thus, from these studies, it appears that exposure to the welding fumes or gases or both caused irritation to the respiratory tract, but not of a sufficient degree to produce significant pulmonary dysfunction (Ref. 18) among current workers. However, the strength of these conclusions is seriously weakened by the bias inherent in point prevalence surveys.

There have been studies in which laboratory animals inhaled welding fumes and gases, or fume concentrate was administered to them intratracheally. Soviet and other Eastern European investigators have observed evidence of pulmonary fibrosis in rats (Refs. 19 through 26) and guinea pigs (Ref. 27) that usually involved experimentation with covered electrodes. It is not possible to implicate a particular agent or agents or to evaluate the importance of these findings because of deficiencies in these experiments, such as failure to report one or more of the following: electrode composition, fume level, fume composition, concentration of gases, and exposure schedule of the animal populations; in addition, dose-response relationships were not investigated.

The pulmonary hazard potential varies with the process and metals being welded. In most situations, fume production is the major source of atmospheric contamination; however, in certain gas shielded welding operations, ozone can be produced in significant amounts. The highest rate of ozone production occurs during GMAW (argon) of aluminum and its alloys (Ref. 28). Significant quantities are also produced in other GMAW and GTAW operations. Because the ozone is not produced in the arc, but is generated over a distance by the action of arc-emitted UV radiation on atmospheric oxygen, ozone removal is difficult. Exposure to welding radiation-produced ozone represents an acute respiratory hazard. The effects of chronic exposure to low levels of ozone in humans are unknown, but, in experimental animals, emphysematous and fibrotic and other pathologic pulmonary changes have been observed (Ref. 29).

Cancer

Epidemiological studies of cancer risk have only incidentally included welders (Refs. 30 through 35). Examination of a mixed group of welders was a specific goal in only one study (Refs. 34 and 35). This was a prospective study of lung cancer in 14 different occupational groups. Other studies involving welders include: a survey by NIOSH (Ref. 30) to examine causes of death in Washington state males; a cohort mortality study in Dow Chemical Company employees including maintenance welders (Ref. 31); a study of lung cancer deaths and cases in Los Angeles County (Ref. 32); and a case-control study of lung cancer patients in 11 California hospitals (Ref. 33). In three of these studies, no correction was made for the confounding effect of smoking (Refs. 30 through 32).

The results of three of the studies (Refs. 30, 32, and 33) indicated that further study of lung cancer in welders was warranted; but, in two of these, neither the effects of smoking nor occupational exposure was examined, and the population of welders was very small in the third. In the most reliable study (Refs. 34 and 35), an increased risk of lung cancer was not observed. Thus, there is no substantial evidence to indicate that exposure to welding byproducts causes lung cancer; reports of well designed epidemiological studies are not yet available.

Significant evidence is not available from epidemiological studies to indicate whether welders are exposed to an increased cancer risk for organs other than lungs. No reliable study of the carcinogenicity of welding fumes and gases in experimental animals has yet been reported.

Eye

Another major concern is effects to the eyes. Injury may be caused by ultraviolet radiation or flying particles, and irritation may be produced by certain fumes and gases (Ref. 36), particularly ozone (Ref. 37). In one Swedish shipyard in 1976, 4,000 welders had 11,000 eye accidents (Ref. 38). In 1977, 7,000 eye injuries in 3,000 welders were reported in another Swedish shipyard, 30 percent of which were due to UV radiation (Ref. 39). Ross (Ref. 40) reported 459 non-lost-time injuries among 400 heavy engineering welders in 1971; 43 percent involved the eye, one third of which were classified as arc eye.

A potential hazard is welding arc radiation. Ultraviolet, visible, and infrared radiation are produced by the welding arc. Welders wearing no eye protection are at risk when the arc is accidentally struck. Assistants and supervisors not adequately protected are also at risk.

Arc eye (or keratoconjunctivitis) is an acute, self-limited irritation and inflammation of the superficial structures of the eye (Refs. 41 and 42), resulting from cumulative unprotected exposure to the UV radiation from the arc (Ref. 43). Cascini (Ref. 44) noted that in 20 cases exposure to the arc lasted 0.33 to 2 hours. The symptoms disappear 22 to 52 hours after the exposure, and no permanent injury appears to remain (Refs. 42 and 45).

Although the eye is not penetrated by the ultraviolet portion of the spectrum, inner structures are affected by wavelengths of 400 to 1400 nm. Radiation in this region of the spectrum can cause lenticular cataracts and chorioretinal burns (Refs. 41 and 46).

Historically, a high incidence of cataracts has been observed in glass blowers and foundrymen after many years of unprotected exposure to radiation emitted by molten glass and metal, respectively (Ref. 41). Massive doses of IR radiation were required to produce lenticular damage in rabbits (Jacobsen et al., 1963, as cited in Ref. 46). This contrasts with the infrequent exposure in modern welders, which, except in cases of gross negligence, is of short duration.

In 1967, Edbrooke and Edwards (Ref. 46) reviewed available evidence and concluded that welders did not develop cataracts more frequently than the general population; unfortunately, no well documented epidemiological study in welders has been published. Although quite rare, cases of retinal damage after unprotected exposure to arc radiation have been reported (Ref. 47).

The distant and near vision of welders does not appear to be significantly different from that of nonwelders, based upon examinations of heavy engineering (Ref. 148) and shipbuilding welders (Refs. 3 and 48) and control groups. However, as in other studies of the eye, these are cross-sectional rather than cohort studies.

Other Organs and Systems

Cardiovascular System

No unusual EKG findings were observed among a mixed group of 402 welders who had at least five years of welding experience and had not been exposed to other pulmonary occupational hazards (Ref. 49). Likewise, EKG abnormalities in 35 shipbuilding welders did not occur more frequently than in a control group (Ref. 3). However, Italian investigators claim that the ratio of the P wave duration to the length of the PR segment was significantly higher in 58 steel arc welders than in controls (Refs. 50 and 51). The EKG should be monitored in future studies.

The blood pressure measurements of welders do not differ from those of nonwelders (Refs. 48 and 52) nor do they have lower blood pressure (Refs. 3, 53, and 54). The latter is possibly due to the fact that welders may be more physically fit than persons in sedentary jobs.

The production of carbon monoxide from carbon dioxide used in gas shielded welding operations and by the oxyacetylene flame is noteworthy. Carbon monoxide avidly combines with hemoglobin to reduce the oxygen-carrying capacity of the blood. Exposure to 100 ppm for 4 hours shortened the time of onset of exercise pain in patients with ischemic heart disease and altered their EKG (Ref. 55). It has been shown to aggravate peripheral arterial disease (Ref. 56) and lowered the threshold for ventricular fibrillation in dogs and monkeys with experimentally-induced heart disease (Ref. 57).

Blood

In 1976, Ross and Hewitt (Ref. 52) found no significant differences in hemoglobin levels between 350 heavy engineering welders and a group of controls. In 1947, Dreessen (Ref. 3) noted no significant differences in hemoglobin levels between 3,000 shipbuilding welders (including both sexes and blacks and whites) and nonwelders. Likewise, in 1964, Marchand et al. (Ref. 49) reported normal hemograms in 402 welders with varied welding experiences, and Schuler et al. (Ref. 58) found no anemia in 23 welders from Santiago, Chile. Thus, under the conditions of the above studies, welding does not appear to affect hemoglobin levels.

Although leukocytosis is reported to be a common finding in metal fume fever (Ref. 59), Chmielewski et al. (Ref. 60) reported normal white blood cell counts in 20 welders before and after they worked on galvanized metal in confined spaces. Also, the leukocyte counts were not different from those of controls among heavy engineering welders (Ross and Hewitt, Ref. 52). Data on other blood parameters are unavailable.

Nervous System

Potential exposure to manganese occurs whenever this metal is used in electrode coatings and cores or in electrode wire. Potential lead exposure occurs during welding and cutting of any metal coated with lead-based paint. Both are poisonous to the nervous system. Information on effects to the nervous system is unavailable, except for those effects attributable to manganese or lead.

Gastrointestinal Tract

Symptoms of metal fume fever include diarrhea, nausea, and abdominal pain (Ref. 60). Chromate, which may be generated in stainless steel welding fumes, is an irritant to mucosal tissue (Ref. 61). Although Dreessen et al. (Ref. 3) noted no increase in gastrointestinal complaints in shipyard welders compared to controls, Rozera (Ref. 62), in a study of 620 Italian metallurgical and metal machining welders, found increased morbidity from ulcerative and other digestive system diseases in them compared to other workers in the industry. Significant corroborating data are lacking.

Other Organs

Except for a few cases of cadmium poisoning, information on effects to the kidneys is unavailable. No reliable reports of adverse effects on liver function were located. One report on a small group of 25 foundry welders revealed no clinical evidence of endocrine dysfunction or significant differences in plasma cortisol, urinary corticosteroids, plasma and urine epinephrine or norephinephrine, compared to 10 controls (Ref. 63).

Welders may be exposed to fluoride dust and vapors from certain FCAW and GMAW operations and SAW fluxes. Chronic fluorosis is a syndrome characterized by increased density of bones and ligaments due to fluoride deposition. However, no data are available that identify a relationship between exposure to fluoride-containing fumes and disorders of bones or ligaments or both (Ref. 64).

Recommendations

Available data are not adequate to reach many conclusions regarding health effects, if any, of the welding experience. Recommendations to fill in the most important information gaps are listed as items 1 through 4 below. In addition, potential health considerations should become an integral part of the development of new welding products; items 5 and 6 are suggested to aid in studying health hazard potential during the development stage.

1. Prospective epidemiological study of chronic lung disease. All of the studies reported to date are of the "cross-sectional" type and are subject to bias from lost workers (Ref. 65). The study should start with a cohort of welders, all employed at the start of the study in the same or similar welding environments; a control group of the same size should be included. Previous occupational exposures, smoking habits, and medical histories should be obtained. The groups should then be followed for a defined period with periodic observation, using symptom questionnaires, chest x-rays, and simple pulmonary function tests. All illnesses and hospitalizations should be carefully documented. All medical examinations and analyses should be performed without knowledge of occupation. Careful environmental monitoring should be pursued so that specific cause-and-effect relationships, if any, can be elucidated (Ref. 18). Increased information can be gained by combining the subject group with an historical cohort, starting 3 to 5 years in the past.

This study would also provide an excellent opportunity to monitor EKG, clinical chemistry, and blood metal levels. The size of the welder and reference groups to be chosen, as well as the duration of the study, depend upon the particular welding environment being examined.

Two milieus should be examined. First, a study of SMA or FCA welding of ferrous alloys is warranted. Such welding is commercially important, and, therefore, large numbers of individuals are potentially exposed. Results of earlier cross-sectional studies indicated that a large population and a long study period (5 years or more) may be required to pick up any effects when good industrial hygiene practices are observed (Ref. 18).

The second group recommended for prospective monitoring are welders using gas metal arc processes where ozone generation is significant. If the atmosphere in this type of welding environment represents a significant health risk, it may be detectable with a smaller sample.

2. Epidemiologic studies of carcinogenic potential. No reliable studies are available that assess the carcinogenic potential of any particular welding situation. Investigation of carcinogenicity will require selection of a cohort of welders and nonwelding controls, in existence far enough in the past that any cancer would have had enough time to develop. A reconstruction of past industrial hygiene measures at the plant under investigation and retrospective collection of relevant personal and occupational information on the subjects (or next of kin) should be undertaken. The incidence and mortality patterns in the exposed and control groups must then be ascertained. Death and morbidity data on other chronic diseases will also be concomitantly obtained.

An increased risk of respiratory tract cancer has been associated with exposure to certain chromates (Ref. 66) and nickel compounds (Ref. 67). Therefore, welders of stainless steel and other chromium and nickel alloys should be studied. The National Cancer Institute is currently sponsoring a study of welders of stainless steel (Ref. 68).

Shielded metal arc or flux cored arc welding of ferrous materials or both account for a major portion of today's welding operations. Therefore, effects of exposure to this milieu in the absence of chromium and nickel (for example, in mild steel welding) should be considered if stainless steel welding is found to be associated with an increased carcinogenic risk.

Results from an epidemiologic study of this design can provide information only on the carcinogenic risk under industrial hygiene conditions and processes that existed 15 to 30 years ago. Therefore, any cancer epidemiology data should be supplemented with information on current exposure conditions (see item 6).

3. Prospective study of eye injuries. Although neither heat cataracts nor retinal injury have been reported to be a problem in welders, published supporting data are poor. Cohorts of current welders should be chosen, and they should undergo periodic eye examination for a length of time sufficient to detect cataract development. If possible, workers who seek other employment should also be followed, since attrition may be due to eye problems. This study might be undertaken independently or as part of item 1.

4. Design of employee records forms. Model forms should be developed to facilitate collecting and centralizing all job description, environmental monitoring, personnel, and other information necessary to monitor the health of welder populations. These should be made available to all firms employing large numbers of welders.

5. Screening of fume for fibrogenic potential. Fume from SMAW and FCAW is a complex mixture composed of unoxidized and oxidized metal from the electrode and material originating from the coating and core, respectively. Although significant evidence of restrictive lung disease was not uncovered in the limited cross-sectional studies discussed above, experiments in animals indicate possible fibrogenic potential.

Silicates constitute a significant portion of many coatings and cores, releasing silica or silicates or both into the fumes when these electrodes are burned. Another source of silica is in the oxidation of alloying elemental silicon. Crystalline forms of silica, which are known to produce pulmonary fibrosis (Ref. 69), have not been found in welding fumes (Refs. 70 and 71). However, even amorphous silica (Refs. 72 through 75, and 305), such as that formed by evaporation from liquid silica (Ref. 72), or amorphous hydrated silica fibrils obtained by acid treatment of chrysotile (Ref. 73) may have fibrogenic potential. Therefore, consideration should be given to fibrogenic potential when developing new electrodes.

Ideally, electrodes should be screened for the fibrogenic potential of their fumes, using a rapid and inexpensive assay. An *in vitro* assay meeting these requirements is the alveolar macrophage test (Refs. 73 and 74). This assay is in the developmental stage and should be first examined for its utility in screening fume condensate.

If the test is validated, electrodes with standard or "typical" coating and core compositions should be developed for such a program, as it is important to be able to correlate biological effects with coating or core compositions. Results on "typical" electrodes can then be made available to aid manufacturers in coating and core formulation.

Based on results of the screening assay, highly suspect fume condensates can be further tested using appropriate experiment animal models. Experimental designs using intraperitoneal (Ref. 73) or intratracheal administration are relatively economical. Chronic inhalation experiments, which more closely mimic the type of exposure potentially received by welders, can be very expensive.

6. Mutagenicity and in vitro carcinogenicity screening of fume condensate. A number of tests are available to screen for mutagenic and carcinogenic potential (Ref. 76). The most well known of these is the Ames test of mutagenicity in *Salmonella.* This test has gained some acceptance because of the good correlation between results in it and *in vivo* carcinogenicity (Ref. 77). However, most results are on organic compounds. Therefore, any test proposed must be validated for solid inorganic compounds.

In the Ames test, samples of stainless steel welding fumes have been found to be mutagenic, whereas fumes from mild steel welding have not (Ref. 78). Based on these results, a study on stainless steel fume in rats has been initiated (Ref. 78). Therefore, process changes that minimize mutagenic potential should be examined for welding stainless steel. After each change, fumes should be collected and bioassayed. Other chromium- and nickel-containing fumes should be examined.

Other *in vitro* assays that measure mutagenic and carcinogenic potential (such as sister chromatid exchange (SCE) or *in vitro* transformation) should also be considered (Ref. 76). Positive screening results in any individual assay or battery of assays should be verified in appropriate animal studies.