

Part II. ARC WELDING FUMES AND GASES

Introduction

Welding fume particles are exceedingly small. Virtually all such particles are smaller than $1.0\text{ }\mu\text{m}$ (micrometers). In previous studies conducted for the American Welding Society, the observers found that a significant fraction of the fumes produced by covered, solid, and tubular or flux cored electrodes contained particles that were smaller than $0.25\text{ }\mu\text{m}$ in diameter.

Such particle size ranges are in substantial agreement with the observations of other investigators. Particle size is important since it is an indication of (a) the depth to which particles will penetrate into the respiratory system and (b) the number of particles that will be retained therein. Welding fume particles are in the size range of particles that penetrate deep into the respiratory system, but they are smaller than particles that are retained with maximum efficiency assuming agglomeration does not occur.

In common with other gases, the gases associated with welding follow the normal laws of diffusion and mix freely with the general atmosphere. They are affected by air movements and by gravity. They pass through the respiratory system along with the other gaseous constituents of the atmosphere.

Origin of Fumes and Gases

Fume generation processes involved during welding are complex and not completely understood. It is generally agreed that the principal mechanism is elemental and oxide vaporization, followed by extremely rapid condensation to form particles. In gas metal arc welding (GMAW), Heile and Hill have suggested that the Mn component comes strictly from elemental vaporization, the Si component from SiO formation, and the Fe component from elemental plus FeO vaporization (Ref. 2.3). Regardless of the precise mechanism, vaporization occurs mainly at or very near the tip of the electrode where the temperature is highest.

The major source of fumes is the metallic part of the electrode and the electrode covering or flux. Only a small fraction of the total quantity of fumes is contributed by the molten weld metal pool because the temperature of the pool is much lower than the temperature at the tip of the electrode. Significant contributions from the base plate can occur, especially if the plate is protected against rusting or corrosion with a metal that has a high vapor pressure: for example, zinc or cadmium.

The constituents in welding fumes can be predicted to a degree on the basis of the composition of the electrode and base metal. If an E70S-3 solid electrode is used for welding carbon steels, iron oxide will be present as the major fume constituent along with small amounts of the oxides of manganese and silicon; copper oxide will be present if the filler wire is copper-coated. If a covered electrode is used for the same purpose, predictions regarding fume constituents are more difficult. The oxides of iron, manganese, and silicon will be present in the fumes, but constituents associated with the electrode covering will also be present. Electrode coverings are quite complex and include gas formers, deoxidizers, binders, slag formers, arc stabilizers, and alloying additions; low hydrogen electrodes contain fluoride compounds as major ingredients. Constituents in the fumes produced by flux cored electrodes are similar to those associated with covered electrodes and are just as difficult to predict.

Welding gases have several origins; depending upon the specific welding process, these include:

- (1) Shielding gas
- (2) Decomposition products of electrode coverings and fluxes
- (3) Reactions of the arc with atmospheric constituents (and atmospheric contaminants)
- (4) Ultraviolet irradiation of the atmosphere

In gas shielded arc welding operations, for example, the most likely source of gases in the welding environment is the shielding gas or its decomposition products. When carbon dioxide is used for shielding, carbon monoxide as well as carbon dioxide may be present in the

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welding area. Similarly, argon will be present when it is used to shield the arc. While argon is not considered toxic, it is heavier than air and can act as an asphyxiant when it displaces atmospheric oxygen in a closed or confined space.

Other gases that may be present include nitrogen dioxide (or other oxides of nitrogen) and ozone. These gases can be formed by the photochemical reaction of ultraviolet radiation from the arc on nitrogen and oxygen in the atmosphere.

Care must be exercised when welding in an area (a) where chlorinated hydrocarbons (e.g., trichloroethylene, perchloroethylene, and others) are used as solvents for degreasing purposes or (b) where vapors from such operations can be carried by air currents. A toxic gas may be formed by photochemical reactions between ultraviolet radiation from the arc and these solvent vapors. Toxic gases can also occur in small amounts as the result of thermal decomposition of such vapors as they pass over hot surfaces (Ref. 2.4). Other toxic gases may be formed by the thermal decomposition of phosphate coatings used to prevent rusting of steel surfaces.

Concerns Regarding the Welding Environment

The presence of fumes and gases in the welding environment is a matter of concern to those responsible for the well-being of welding personnel. Since constituents are a potential hazard to the health of the welder, potential problems can be anticipated by estimating the concentrations of fume and gas constituents in the welding area and comparing these data to established exposure standards.

To consider a concrete example: it will be assumed that fumes are being generated at the rate of 0.40 g/min during the semiautomatic gas metal arc welding of carbon steel with an E70S-3 electrode in an unventilated room with a volume of 283 m³ (10 000 ft³). If it is assumed that such fumes diffuse uniformly throughout the room (a simplistic assumption, since fume particles are subject to gravitational and other forces), the total fume concentration in the room will exceed the established threshold limit value, TLV, as defined by the American Conference of Governmental Industrial Hygienists (ACGIH) of 5 mg/m³ for not otherwise classified total fume particulates in about 3.5 minutes. Ventilation provided at the rate of about 85 m³/min (3000 ft³/min) should be sufficient to maintain the fume concentration below 5 mg/m³ indefinitely.

To examine this example further, it will be assumed that the composition of the fumes is as follows:

Element (oxide)	Amount, weight percent
Fe (Fe ₂ O ₃)	63 (90.0)
Mn (MnO)	5 (5.2)
Si (SiO ₂)	2 (4.3)
Cu (CuO)	0.4 (0.5)

With a total fume generation rate of 0.40 g/min and uniform distribution of the fume constituents in the room, the time required to exceed the ACGIH time-weighted-average threshold limit values (TWA-TLV) for the constituents listed above is shown in the following table:

Constituent	TWA-TLV, mg/m ³	Time to exceed TWA-TLV, min.
Fe ₂ O ₃	5	3.9
Mn	5	70.8
SiO ₂	2*	32.9
Cu	0.2	70.8

*Amorphous, respirable.

The tabular data indicate that iron oxide is of most concern from the hygienic viewpoint, because the time for this compound to exceed its limiting value is the shortest.

As has been observed, the assumption that the fumes are dispersed uniformly throughout the welding area may be in error since the fume particles possess mass and are subject to settling. Fume concentrations are highest in the immediate welding area during the actual welding operation. Nonetheless, an example of this nature is useful in demonstrating possible problem areas.

Existing Literature

The technical literature of the past two decades contains numerous references to research conducted to (a) sample fumes and gases in the welding area, (b) determine individual fume and gas constituents, and (c) calculate concentrations of these constituents for comparison with recognized allowable limits. Many of these references are included in the AWS publication, *The Welding Environment* (Ref. 5). These investigations generally had limited objectives because they were undertaken to study the fumes associated with a particular welding application, to evaluate a specific electrode, to assess the performance of a ventilation system, or for some other definite purpose. The usefulness of some of this work is questionable today because supporting data on welding procedures, sampling methods, and analytical techniques are often incomplete or totally lacking. Nonetheless, these studies are important because the results form the basis for much of today's knowledge.

Until recently, little data were available that could be used to determine the rate at which fumes are produced as a function of welding process, welding conditions, consumables, and other variables. The lack of such data is due in part to the difficulties associated with determin-

4. Note that the value accepted by OSHA for iron oxide, the major constituent in the fumes produced during the welding of steel, is 10 mg/m³. See General Industry Safety and Health Regulations Title 29 CFR Part 1910.1000.

ing fume generation rates accurately. This information is valuable to those engaged in the layout of welding areas and the design of ventilation systems as well as those concerned with the health, safety, and comfort of welding personnel. Some of the more significant investigations are reviewed below; the cited references should be consulted for additional details.

Kobayashi, Maki, and Ohe investigated the fumes produced by several electrodes used for shielded metal arc welding and determined fume generation rates as a function of the type of electrode covering (ilmenite, lime, titania, and iron powder) and selected process variables (current, voltage, power, electrode polarity, and welding speed) (Ref. 2.5). In the course of these studies, equations were developed to show the dependence of fume generation rate on welding current. For electrodes with ilmenite or lime coverings, the rate increased almost in proportion to the square of the welding current. For electrodes with lime-titania coverings, the rate increased almost linearly with current. Increases in arc voltage (or arc length) were accompanied by significant increases in fume generation rate.

Swedish investigators developed procedures to determine fume generation rates for various types of electrodes to obtain data for use in establishing a system for classifying electrodes according to a calculated theoretical air requirement factor (Refs. 2.6, 2.7). The magnitude of this factor depends upon the weight of each potentially hazardous fume constituent as well as on the fume generation rate.

Studies were conducted by Heile and Hill to investigate the fume generation and metal deposition characteristics of electrodes used for shielded metal arc welding, flux cored arc welding, and gas metal arc welding (Ref. 2.3). These data and those obtained from analyses of fume and thermodynamic calculations were used to support theoretical concepts for the mechanisms of fume generation. Elemental vaporization, condensation, and oxidation-enhanced vaporization processes appeared to control fume generation during welding.

Other investigations concerned with the mechanisms of fume generation during shielded metal arc welding were conducted by Kobayashi, Maki, Hashimoto, and Suga (Ref. 2.8, 2.9). Using a high-speed motion picture camera, evidence was obtained that fumes originated at the tip of the electrode and were propelled away from the tip by magnetic forces. Various tracer metals (manganese, chromium, and nickel) were used to determine the contributions of the core wire, electrode covering, and base metal to the total fume production rate. Only a small fraction of the fumes originated in the molten weld metal pool.

Morita and Tanigaki measured the fume generation rates of 60 different covered electrodes used for welding carbon and low alloy steels (Ref. 2.10). Fume generation rates were highest for electrodes with cellulosic coverings; rates were lower for electrodes with low-hydrogen, mineral, and iron powder iron oxide coverings. By correlating these data with the composition of the

fumes, electrode coverings, and slags, a relationship between fume generation rates and the presence of specific elements and compounds was established. This information was used in the development of several experimental electrodes with low fume generation rates.

Recent Soviet research has been directed toward determining the fume generation and metal deposition characteristics of electrodes used in various welding processes. Katrenko, Kassov, and Karpenko investigated the effect of slag-forming constituents in flux cored electrodes on the fume generation rate and the weight of fumes as a function of the weight of deposited metal (Ref. 2.11). The effect of various shielding gases on the fume generation characteristics of electrodes used in the gas metal arc welding of ferrous metals was studied by Erman and Kabasin (Ref. 2.12) and by Vorontsova and Mosolov (Ref. 2.13). The fume generation characteristics of aluminum gas metal arc welding electrodes have been determined by Psaras and Popova (Ref. 2.14). In a related investigation, Erman demonstrated that the fume generation rate for an aluminum electrode was lower during pulsed arc welding than during conventional gas metal arc welding (Ref. 2.15).

Studies of various types of electrodes have also been conducted by Pantucek to establish an electrode classification system based on fume generation rates and fume compositions (Ref. 2.16).

Of these investigations, the one conducted by Heile and Hill was most useful in the AWS program because experimental data were obtained with many of the same domestic electrodes. Data from this paper have been incorporated in this report wherever they served to supplement or assist in the interpretation of the experimental results. The results of foreign studies are useful because they indicate trends in expected fume generation rates when welding is done with electrodes similar to those produced domestically.

Data on fume generation rates are often based on the weight of a sample that represents only a fraction of the total amount of fumes produced during welding. As a result, sample weights are subject to variations caused by inconsistencies in the sampling procedures and in the behavior of the fume plume. The laboratory procedures used in this investigation were established to minimize these sources of error by collecting all the fumes produced during a measured interval of welding.

Scope

This task was designed to provide basic information on the fume generation characteristics of commonly used arc welding electrodes as a function of welding process, electrode classification, and selected operation variables. It emphasized a comprehensive laboratory investigation of arc welding fumes to determine the rate at which they are produced with selected welding conditions in order to relate the fume generation rate to various electrode characteristics. More limited studies were also conducted

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to (a) detect gases in the welding area, (b) determine fume compositions, and (c) characterize fume particles in terms of size, crystalline structure, etc. Such data will be useful to industry in planning industrial hygiene programs and determining ventilation requirements.

At the request of the AWS Research Committee, a short study was made to investigate the influence of humidity in the sampling area on fume sampling results. This study is reported in Section II E.

Limitations

Detailed laboratory investigation of the fume generation characteristics of representative electrodes was restricted to the following processes:

- (1) Shielded metal arc welding
- (2) Flux cored arc welding
- (3) Gas metal arc welding
- (4) Gas tungsten arc welding

Research was also conducted to investigate the fume generation characteristics of selected electrodes as a function of various process variables: current, voltage, arc length, etc.

During the course of this investigation, limited research on fume particle characterization, fume analysis, and gas detection during welding was included.

Program

Fume generation rates were determined for all electrodes under study under selected operating conditions. Relationships were also established between this rate and various electrode characteristics (melting rate, metal deposition rate, etc.) to obtain data that could be used effectively by welding engineers, industrial hygienists, ventilation specialists, and others concerned with the health and safety aspects of arc welding.

Equipment, Materials, Procedure

Fume Collection Chamber

The Battelle fume collection chamber is a sheet metal structure with a volume of about 33 ft³ (0.93 m³). The upper portion of the chamber tapers inward to form an area in which the filters and holder are located; the fumes are removed from the chamber by an exhaust blower attached to the exit side of the filter holder by flexible ducting. The chamber can be sealed to prevent the leakage of fumes during the sampling interval.

The chamber is equipped with a variable-speed turntable on which the workpiece is placed. A steady-rest is provided to assist the welder in maintaining a constant arc length during welding. The welding torch is manipulated by means of a glove port. Several holes are located around the base of the chamber to insure a positive flow

of air through the structure during welding and sampling. Views of the chamber are shown in Figs. 2.1A and 2.1B.

Filter System. Samples of the total fumes produced during welding were collected with an assembly consisting of an absolute filter preceded by a prefilter.

Absolute Filters. Glass fiber absolute filters with a high capture efficiency for particles below one micrometer in size were used because they were well-suited for gravimetric analysis and could retain large quantities of fume particulates. Also, moisture pick-up problems were minimal with these filters, since they were non-hygroscopic. However, glass fiber filters are ill-suited for chemical analysis because it is difficult to separate the fume particles from the filter mesh. The absolute filters were 8 by 10 in. (0.20 x 0.25 m) in size.

Prefilter. Despite the ability of glass fiber absolute filters to capture and retain large amounts of fumes, they were subject to clogging or overloading. To eliminate this problem, a prefilter consisting of two layers of glass fiber insulation was placed in front of the absolute filter.

Analytical Samples. Fume samples were also collected for chemical analysis. Cellulose membrane filters with a pore size of 1.2 micrometers were used for this purpose because such filters could be ashed, dissolved, or otherwise treated to recover the fumes for analysis. Since the amount of fumes that could be retained by membrane filters without clogging was limited, these filters were also preceded by a glass fiber insulation prefilter.

The fume collection area of the chamber is shown in Fig. 2.1C; the filters are shown in Fig. 2.1D.

Other Equipment

Welding with covered electrodes was done with a conventional motor-generator power unit and a standard electrode holder.

For welding with wire electrodes, a torch with a water-cooled nozzle was mounted in the fume collection chamber on a steady-rest that permitted the operator to maintain the selected electrode stickout. Power was supplied by a constant potential source and a commercial wire feeder was used to feed wire at the desired rate.

Current and voltage were continuously monitored during welding operations. Since voltage was measured between the wire feeder and base plate, the measurement included the voltage drop in the welding torch and cables as well as the drop across the arc.

Electrodes

The fume generation characteristics of electrodes in a single classification were generally determined by evaluating three electrodes, each made by a different manufacturer. Only one or two electrodes per classification were evaluated in a few instances when the number of manufacturers producing a particular electrode was limited (some nickel-base electrodes) or when the evaluation of more than one electrode appeared to be unnecessary (solid electrodes used for gas metal arc welding).

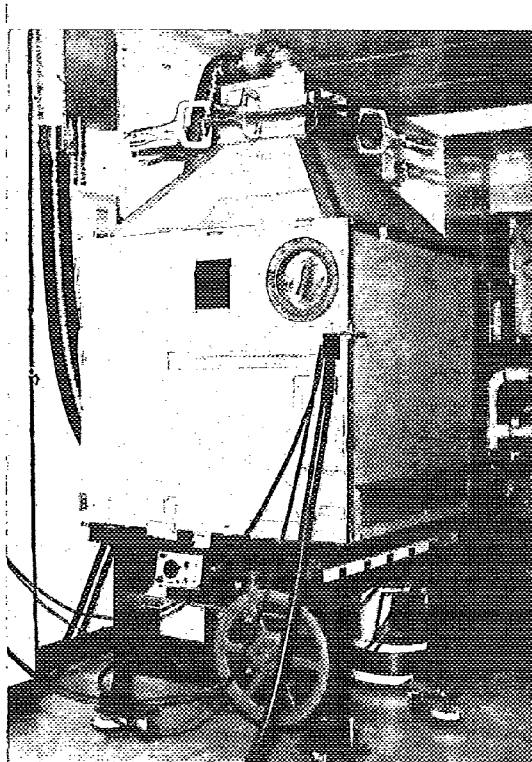


Fig. 2.1A—Fume collection chamber

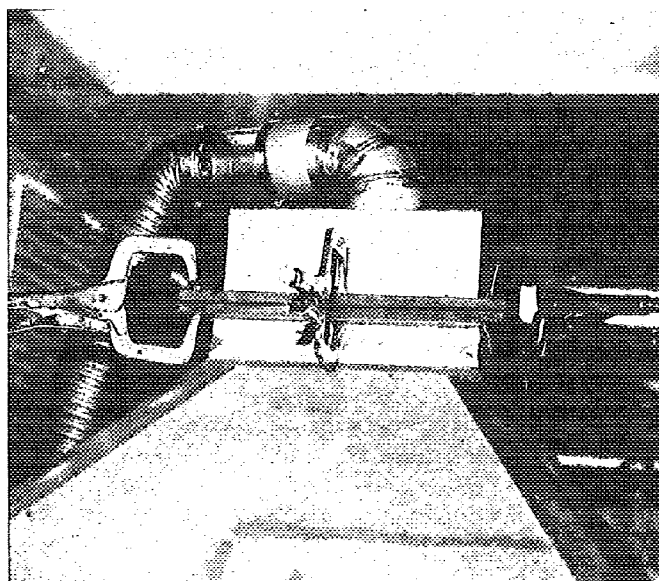


Fig. 2.1C—Fume collection section

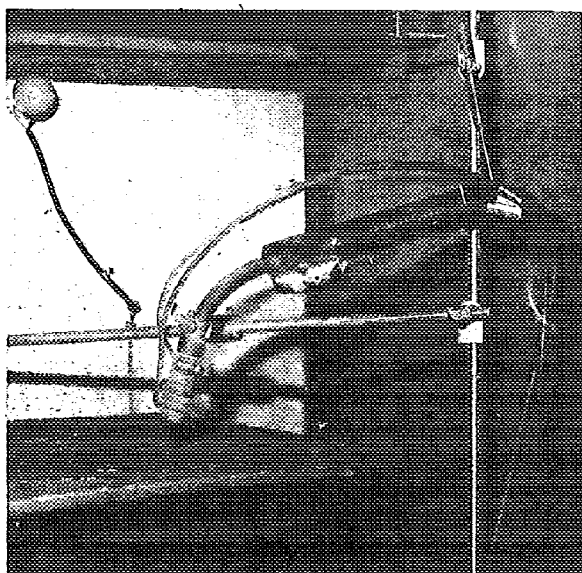


Fig. 2.1B—Torch arrangement inside chamber

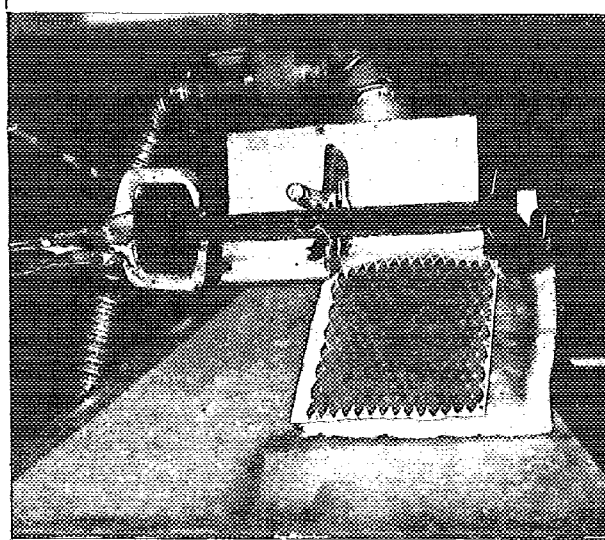


Fig. 2.1D—Collection area with a used absolute filter and glass fiber prefilter

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The electrodes used in this investigation were obtained from local commercial sources. Electrodes used for some specific studies (e.g., studies of the fumes produced by electrodes with different diameters) were obtained from one manufacturer.

The electrodes included in this investigation are listed in Appendix A, along with the purposes for which they were used.

Section IIA, Laboratory Test Method

Under the guidance of the AWS Research Committee, a laboratory test method was established to study the fumes associated with arc welding and related processes. Specifically, this method was designed for the laboratory collection of total fume samples in order to determine fume weight as a function of welding time, various electrode characteristics, and procedural variables.

Procedures

Experimental procedures were established to determine the fume generation characteristics of electrodes used in various arc welding processes by gravimetric analyses of fume samples. Samples of the fumes produced by specific electrodes were collected in triplicate to average the inconsistencies of sampling; in some instances, one or two extra samples were collected to obtain additional data or to verify specific results. With appropriate changes to fit the process, the sampling procedures were generally applicable to cutting and spraying as well as arc welding.

After the desired welding conditions were established, the fume samples were collected in accordance with the following procedures:

- (1) The filter-prefilter assembly was weighed to 0.1 mg on an analytical balance.
- (2) The filter-prefilter assembly was placed in the holder at the apex of the fume collection chamber, the sealing gaskets were installed, and the holder was clamped in place.
- (3) The chamber was sealed and the blower that exhausted the fume chamber was turned on. Immediately thereafter, a bead-on-plate weld was made. The welding interval was one-half to one minute, depending on the expected fume generation rate.
- (4) With the blower functioning, fumes were collected until the chamber atmosphere was clear.
- (5) The filter-prefilter assembly was weighed immediately after its removal from the filter holder to determine the fume weight.

The following were recorded during sampling: (a) filter-prefilter weight before and after sampling, (b) welding conditions, and (c) electrode physical characteristics (diameter, length, and weight of electrode consumed).

To avoid problems caused by the pickup of moisture by the absolute filter, prefilter, or fume sample, welding and sampling were done in a clean room where temperature and humidity could be controlled. Also, glass fiber

filters were used because they were nonhygroscopic. Nevertheless, moisture pickup was possible in view of the long periods (15 to 30 minutes) during which fume samples were collected. To examine this possibility, fume samples were collected in accordance with (a) established procedures and (b) procedures in which the filter-prefilter was baked before each weighing operation to remove absorbed moisture. Moisture did not appear to be a problem, because there was essentially no difference in the fume weights. However, the possible effects of moisture pickup on the accuracy of experimental data should be considered if welding and sampling are done in a high humidity area. Additional information on the effect of humidity is given in Part IIE of this report.

Procedures were also established to measure the metal deposition rate during welding. To obtain these data, bead-on-plate welds were deposited on small sections of plate that were weighed before and after welding to determine the amount of metal deposited during the welding interval. In the case of welds made with shielded metal arc or flux cored arc welding electrodes, slag was removed before the weighing operation.

Chamber Evaluation

Studies were conducted to evaluate the performance of the Battelle fume collection chamber and filter system. To provide a common basis for comparing the performance of this chamber with that of equipment designed and used by members of the AWS Research Committee, these studies were undertaken using specific lots of E7018 and E70T-1 electrodes set aside for this purpose. To further insure comparability, the welding conditions used by the subcommittee members for each of the respective electrodes were also used by Battelle; these conditions are shown in Table 2.1A. The data obtained by the AWS Research Committee and by Battelle are presented in Table 2.1B. When the differences in equipment and sampling procedures are considered, the agreement among the data is good.

During the program, the Battelle fume collection chamber and filter system performed well, and consistent results were obtained. In replicate sampling experiments, the fume generation rates varied by only 1 or 2 percent. The variation in calculated quantities (e.g., weight percent of electrode converted to fumes, weight of fumes per weight of deposited metal, etc.) was somewhat greater but generally less than 4 percent. These observations were confirmed by the small standard deviations associated with each group of data.

As indicated, fume samples were collected in triplicate for all of the electrodes evaluated. For any given electrode, these samples were collected one after another under the same welding conditions, and there was little variation in the individual fume sample weights. More variation would be expected if the sampling was made at random and the welding conditions were changed after each fume collection experiment.

Experimental Results

Figures and short tables are used throughout this report to summarize the data and assist in the interpretation of the results. Data on the fume generation characteristics of arc welding electrodes are presented in detailed tabular form in Appendix B. In addition to the fume generation rate for specific electrodes, these sheets contain information on (a) the conditions under which the experimental data were obtained, (b) the melting and metal deposition rates of the electrode, and (c) calculated quantities that relate the amount of fumes produced during welding to the metal deposition rate and other electrode characteristics.

Fume generation rates are expressed in "measured" and "normalized" values. The normalized value provides a means for minimizing the effects of unintentional variations in welding current on fume generation rate.

Normalization was accomplished by relating the fume generation rate to the current squared. Figure 2.9 shows the relation of I^2 trend lines and data for two covered electrodes, one cored electrode, and one solid wire electrode. It is apparent that the current-squared normalization will fit a wide variety of fume generation data.

The fume generation rate is most important because it is a direct measure of the amount of the fumes produced during welding under specified conditions. This information can be used effectively by welding engineers, industrial hygienists, ventilation specialists, and others. Of equal importance is the calculated factor "weight of fumes per unit weight of deposited metal," because it can be used to estimate the amount of fumes that will be produced during production welding operations. This factor also provides a convenient means to compare welding processes on a fume-produced to weight-of-deposited-metal basis.

Table 2.1A
Welding conditions for E7018 and E70T-1 electrodes

Parameter	E7018		E70T-1	
	AWS Subcommittee on Sampling	Battelle	AWS Subcommittee on Sampling	Battelle
Current, A	140	135-145	450-470	420-450
Voltage, V	---	23-24	30	30-31
Wire feed rate, in./min (mm/s)	---	---	87.21 (206)	87.00 (205.5)
Welding speed, in./min (mm/s)	5.93 (14)	5.93 (14)	6.77 (16)	6.77 (16)
Shielding gas	---	---	CO ₂	CO ₂
Gas flow rate, ft ³ /h (liters/min)	---	---	19-21 (40-45)	21-24 (45-50)
Electrode stickout, in. (mm)	---	---	32 (1.25)	32-35 (1.25-1.37)
Weld time, s	---	60	---	15 and 30
Electrode polarity	Positive	Positive	Positive	Positive

Table 2.1B
Fume generation characteristics of E7018 and E70T-1 electrodes
(AWS Research Committee and Battelle data)

Characteristics	E7018				E70T-1			
	AWS Subcommittee on Sampling			Battelle	AWS Subcommittee on Sampling			Battelle
	A	B	C		A	B	C	
Fume generation rate, g/min	0.50	0.52	0.43	0.51	1.15	1.05	1.27	1.26
Weight percent electrode converted to fumes	1.54	1.79	1.47	1.62	0.75	0.70	0.83	0.85
Melting rate, kg/h (lb/h)	---	---	---	---	---	9.00 (19.8)	9.17 (20.2)	8.90 (19.6)

Section IIB. Fume Generation Characteristics of Arc Welding Electrodes

Baseline Data

Research was conducted to obtain baseline data⁵ on the fume generation characteristics of representative covered, flux cored, and solid electrodes used for welding carbon and low alloy steels, stainless steels, nickel and other high alloy base metals, copper alloys, and aluminum alloys. To obtain results of value to those engaged in production welding operations, welding was done at currents in the mid-to-upper portion of the range recommended by the electrode manufacturer. Some welding was done under less ideal conditions with selected electrodes to study the effect of process variables on the fume generation characteristics.

Fume Generation Rate Versus Welding Current. Experimental evidence indicates that the fume generation rate varies in accordance with a power function of current. Kobayashi, Maki, and Ohe determined the fume generation rates for a series of ilmenite, lime, and lime-titania covered electrodes with diameters ranging from 3.2 to 6.0 mm (0.128 to 0.240 inch) at appropriate current levels (Ref. 2.5). In analyzing the data, they observed that the fume generation rate (FGR) for the electrodes in each classification could be related to welding current, I , by an equation of the form

$$FGR = aI^b$$

where b had a value between 1.17 and 1.73. While the equations representing the fume generation behavior of the electrodes in each classification differed in accordance with the electrode covering, their similarity indicated the general dependency of fume generation rate on a power function of current.

In the present research program, this type of analysis was expanded to derive a general equation relating the fume generation rate for carbon and low alloy steel covered and flux cored electrodes to the baseline welding current. This grouping was used because there are similarities between these electrodes, particularly in the compositions of the respective coverings and fluxes. For example, Smith indicates that the high titania E6013, E7014, and E7024 covered electrodes are similar to the E70T-1 and E70T-2 flux cored electrodes in terms of the type of covering and flux, slag composition, and weld metal characteristics (Ref. 2.17).

5. Baseline data are those data collected when electrodes were operated at currents in the mid-to-upper part of the manufacturer's recommended operating range.

Data on the fume generation rates of 4 mm (5/32 in.) diameter covered and 2.4 mm (3/32 in.) diameter flux cored electrodes used for welding carbon and low alloy steels are plotted in Fig. 2.2 as a function of welding current. Studies to fit the data to a power function of current showed that the fume generation rate can be expressed as a function of $I^{1.27}$ with a correlation coefficient (r^2)⁶ of 0.77. The magnitude of the correlation coefficient indicates a strong dependence of fume generation rate on current. This function is in general agreement with the results obtained by Kobayashi, Maki, and Ohe (Ref. 2.5) and lends credence to the concept that approximate fume generation rates for similar covered and flux cored electrodes can be predicted by a power function of welding current.

The line shown in Fig. 2.2 represents an $I^{1.27}$ regression line. The fume generation rates associated with two E6010 electrodes were much higher than those indicated by the regression line. These high fume generation rates were a result of running tests with excessively long arc lengths. The effect of arc length and other process variables on fume generation rate is discussed later in this report.

Data obtained from several studies in the course of this program are presented in Fig. 2.3. (The figure contains an I^2 regression line for comparison.) Included are fume generation rates as a function of current for the following electrodes:

- (1) E6010, E6013, and E7018 covered electrodes with diameters ranging from 2.4 mm to 4.8 mm (3/32 in. to 3/16 in.) (Tables B30 through B33)
- (2) E7018 and E7024 electrodes, 6.4 mm (1/4 in.) in diameter, at high welding currents (Table B40)
- (3) Stainless steel covered and flux cored electrodes with diameters of 4 mm (5/32 in.) and 2.4 (3/32 in.), respectively (Tables B7, B8, B9, and B15).

These data points fall within a fairly narrow band. It appears that the fume generation rates for such electrodes will generally lie within a narrow band approximating the regression line, if the electrodes are used in accordance with the manufacturer's recommendations.

Fume generation rates measured by Heile and Hill (Ref. 2.3) and Kobayashi, Maki, and Ohe (Ref. 2.5) were also plotted to determine the agreement between these data and the baseline data developed during this program.

6. The correlation coefficient (r^2) is an indication of the fit between the derived curve and the experimental data. If the dependency between fume generation rate and current is strong, the correlation factor will be close to 1 or -1. If the dependency between these variables is weak, the coefficient will be close to 0.

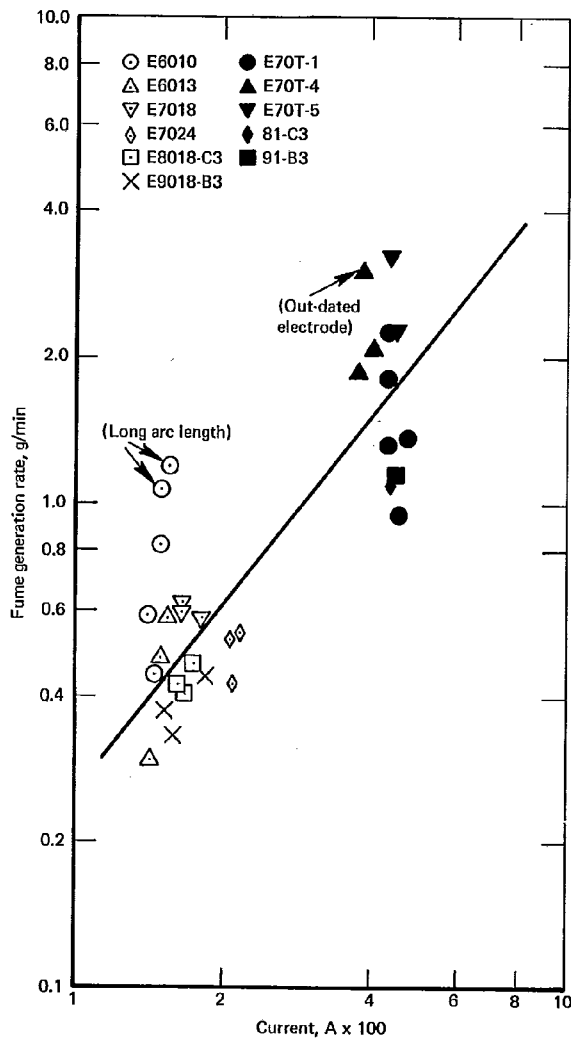


Fig. 2.2—Fume generation rates for covered and flux cored electrodes used for welding carbon and low alloy steels as a function of current

Heile and Hill evaluated the fume generation characteristics of several carbon steel covered electrodes at conventional welding currents, and the resulting data are presented in Fig. 2.4. Kobayashi, et al., investigated electrodes with ilmenite, lime, and lime-titania coverings; data associated with ilmenite coverings are included in this figure. These data also fit the I^2 regression hypothesis reasonably well. In addition, the AWS program data agree well with those developed by the other investigators.

Fume Generation Rate Relative to Electrode Type.

The preceding overview of the baseline data has been primarily concerned with (a) the fume generation rates of various classifications of steel covered and flux cored electrodes and (b) an examination of the dependency of fume generation rate on welding current. Grouping of the electrodes in this manner was logical because covered and flux cored electrodes have much in common and because the covering (or flux) as well as the base metal contributes toward the formation of fumes. Data obtained from studies of solid gas metal arc electrodes were not included, because these electrodes do not incorporate a flux and the data could not be compared on an equal basis.

To examine the data obtained for all classifications of electrodes investigated during this program, the results for the following important fume generation characteristics are summarized in Fig. 2.5 and Table 2.2: (a) fume generation rate and (b) ratio of the weight of fume to the weight of deposited metal. Fume generation rate provides an immediate and direct indication of the amount of fumes to which a welder may be exposed. The ratio of the weight of fumes to the weight of deposited metal can be used to compare electrodes or welding processes on a fume exposure basis.

Under the "covered electrode" heading in Fig. 2.5, for example, the "steel" category includes electrodes that are used for welding carbon and low alloy steels: i.e., E6010, E6013, E7018, E7024, E8018 C3, and E9018 B3. The electrodes within any category can be determined from Table 2.2. Data on the fume generation characteristics of individual classifications of electrodes will be reviewed later.

A large quantity of experimental data has been compressed into Fig. 2.5 and its usefulness depends on the care with which it is interpreted. Ranges of fume generation rates and ratios of weight of fume to weight of deposited metal that may be observed when specific base metals are welded with covered, flux cored, and solid electrodes are evident in this figure. However useful this information may appear from the health and safety viewpoint, it must be used cautiously. For example, this figure indicates the fumes were produced at the highest rate when carbon and low alloy steels were welded with flux cored electrodes, and it would appear that problems associated with fumes could be minimized by using covered or solid electrodes. This may or may not be the case, since this conclusion does not consider the effects of the electrode and process variables on fume generation characteristics. When examining these data, the following should be considered:

(1) Fume generation rates are highly dependent on the welding current. Currents for flux cored arc welding were much higher than those used for welding with covered electrodes (Table 2.2). As a result, more fumes were produced during flux cored arc welding. However, since metal deposition rates were higher too, the ratio of weight of fume to weight of deposited metal was lower

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for some electrodes during flux cored arc welding than it was when welding was done with certain covered electrodes. The range for this ratio even overlapped a portion of the range associated with gas metal arc welding electrodes which are recognized as low fuming types.

(2) The data in Fig. 2.5 were obtained with electrodes whose diameters were as follows: 4 mm (5/32 in.) for covered electrodes, 2.4 mm (3/32 in.) for flux cored electrodes, and 1.1 mm (0.045 in.) for most of the solid electrodes (a few of the solid electrodes had diameters of 0.8 mm [0.030 in.]). Since recommended current ranges are largely based on electrode diameter, fume generation characteristics will change if diameter and current are increased or decreased. As an example, when 6.4 mm

(1/4 in.) diameter electrodes were evaluated at currents near 400 A, fume generation rates were about the same as those produced by flux cored electrodes with diameters of 2.4 mm (3/32 in.) when operated at about the same current level.

(3) Other variables (arc length, electrode polarity, etc.) affect fume generation characteristics appreciably. The effects of such variables are not reflected by the data in Fig. 2.5.

Many factors must be considered when the data in Fig. 2.5 are reviewed. Electrodes are selected on the basis of economic and technical considerations (cost, weld metal properties, deposition rate, etc.), and not on the basis of their fume producing propensities. Should

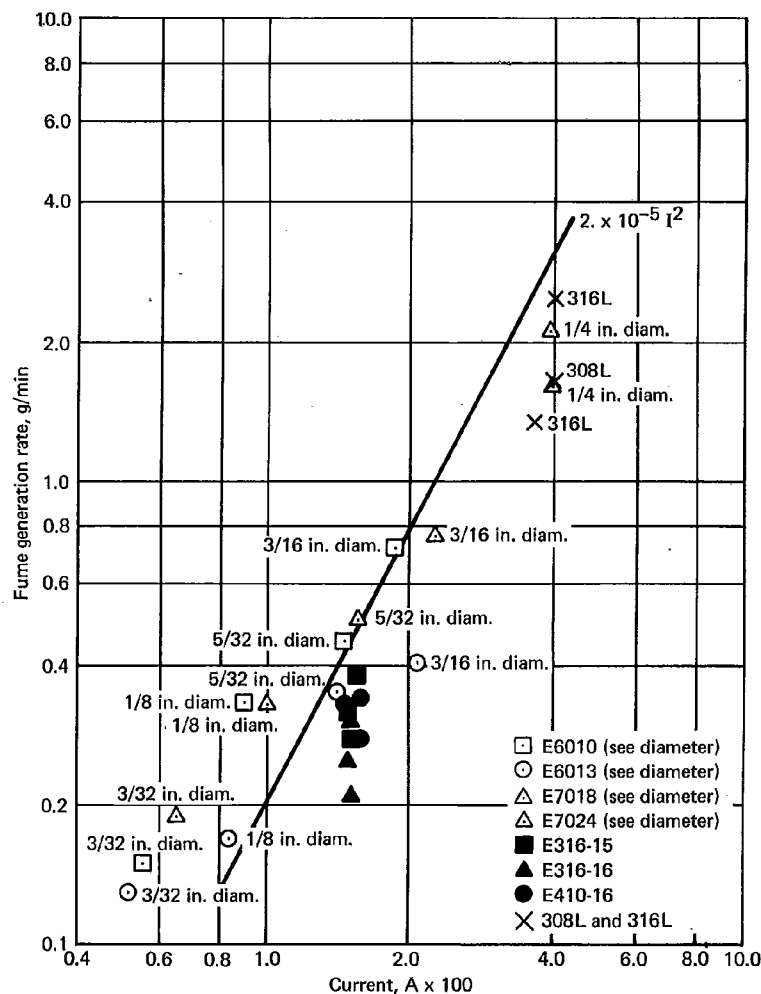


Fig. 2.3—Fume generation rates for carbon and stainless steel covered electrodes as a function of current

the occasion arise to include fuming characteristics among the selection criteria, full use should be made of Table 2.2 (and the more detailed tables in Appendix B) to interpret the data in Fig. 2.5 properly.

Covered and Flux Cored Electrodes

In this section, data obtained at recommended operating conditions are reviewed for covered and flux cored electrodes. These electrodes are considered together because they constitute a metal-flux system, and the amount of fumes produced during welding is dependent upon the flux as well as the metallic part of the electrode.

Covered Electrodes

Fume Generation Characteristics. Data on (a) fume generation rates and (b) ratios of weight of fumes to weight of deposited metal obtained during studies of carbon steel, low alloy steel, stainless steel, nickel, and other high alloy covered electrodes are shown in bar graphs in Fig. 2.6. All of the electrodes were 4 mm (5/32 in.) in diameter and welding was done at current in the mid-to-upper part of the recommended operating range. In most instances, three electrodes made by different producers were evaluated per classification; one electrode per classification was studied in the case of the nickel and other high alloy electrodes. The data upon which this figure is based are shown in Table 2.2; detailed information on welding conditions and fume generation characteristics is contained in Tables B1 through B10.

The trends in fume generation rates and ratios of weight of fumes to weight of deposited metal shown in Fig. 2.6 are in general agreement with those obtained by other investigators (Refs. 2.3 and 2.5). The following data for electrodes with the same diameter as those examined during the AWS program were obtained by Heile and Hill:

Electrode classification	Current, A	Fume generation rate, g/min.	Weight of fume/wgt. of deposited metal, g/kg
E6010	110	0.32	19
E6010	170	0.66	24
E7018	160	0.28	8
E7018	220	0.65	18
E7024	180	0.29	8
E7024	230	0.47	8

At comparable welding currents, these data fell within or near the ranges shown in Fig. 2.6.

The data in Fig. 2.6 must be interpreted carefully because they were obtained by evaluating 4 mm (5/32 in.) diameter electrodes under conditions based on the various

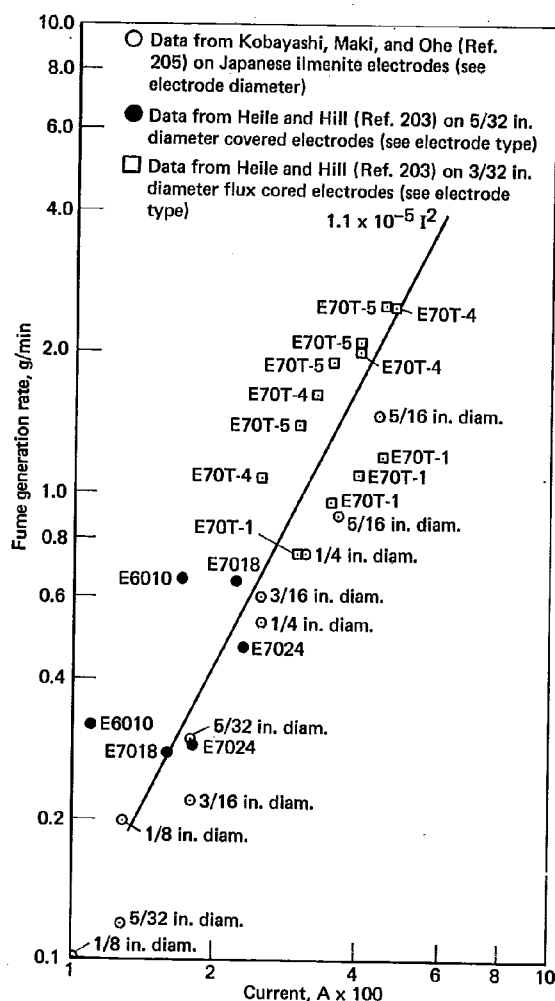


Fig. 2.4—Fume generation rates obtained by other investigators with carbon steel covered and flux cored electrodes as a function of current

manufacturers' recommendations. Data differing from those shown in Fig. 2.6 will be obtained if the electrode diameter or welding conditions are changed.

Fume generation rates and ratios of weight of fume to weight of deposited metal were somewhat higher for E6010 electrodes than for the other covered electrodes, but there was considerable overlapping of the ranges for these quantities. Several carbon and low alloy steel electrodes had fume generation rates that fell within the lower portion of the range associated with E6010 electrodes. It is interesting to note that the fume generation

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Table 2.2
Summary of baseline fume generation data for arc welding electrodes

Electrode classification	Number of electrode brands evaluated	Current range, A (nominal)	Average range		Source table-App. B
			Fume generation rate, g/min	Weight of fumes/weight of deposited metal, g/kg*	
Shielded metal arc covered electrodes					
Carbon and low alloy steel					
E6010	3	140-150	0.83 (1.20)**	35.85 (54.36)**	B1
E6013	3	145-160	0.31-0.58	14.16-25.75	B2
E7018	3	170-180	0.57-0.60	20.35-21.83	B3
E7024	3	200-230	0.43-0.55	8.92-11.11	B4
E8018 C3	3	160-175	0.43-0.47	15.92-17.82	B5
E9018 B3	3	160-180	0.36-0.46	11.19-14.94	B6
Stainless steel and high alloy					
E316-15	3	150-155	0.28-0.38	8.02-11.08	B7
E316-16	3	145-150	0.21-0.31	6.56-11.92	B8
E410-16	3	145-160	0.28-0.34	11.75-13.97	B9
ENi-CI	1	135	0.37	12.90	B10
ENiCU-2	1	145	0.31	10.08	B10
Inconel 625	1	140-155	0.32	9.24	B10
Haynes C-276	1	130-135	0.37	14.20	B10
Haynes 25	1	135-140	0.26	8.94	B10
Flux cored electrodes					
Carbon and low alloy steel					
E70T-1	5	435-485	0.96-2.27	6.65-17.51	B11
E70T-4	3	370-390	1.86-2.09(2.98)**	12.76-13.83(22.70)**	B12
E70T-5	2	425-450	2.26-3.25	17.87-23.63	B13
81-C3	1	440-445	1.11	8.69	B14
91-B3	1	450	1.15	8.42	B14
Stainless steel					
E308LT-3	1	440-445	1.64	9.11	B15
E316LT-3	2	340-405	1.34-2.48	6.97-12.32	B15
Gas metal arc solid electrodes					
Carbon steel					
E70S-3	3	260-290	0.41-0.46	4.97-5.68	B16
Spray w/Ar-2 O ₂	3	260-290	0.41-0.46	4.97-5.68	B18
Spray w/Ar-9 CO ₂	3	205-225	0.41-0.49	6.39-8.34	B16,B18
Globular w/CO ₂	3	320-330	0.45-0.51	3.09-3.31	B16,B18
Short circuit w/Ar-25 CO ₂	3	195-205	0.20-0.25	4.11-4.91	B16,B18
E70S-5					
Spray w/Ar-2 O ₂	1	275-290	0.38	5.01	B19
Globular w/CO ₂	1	325-345	0.40	2.61	B19
Short circuit w/Ar-25 CO ₂	1	210-215	0.24	4.28	B19
Stainless steel and high alloy					
ER316	1	165-175	0.04	0.58	B20
ERNiCu-7	1	250-260	0.16	2.02	B21
Inconel 625	1	190-195	0.06	0.87	B21
Haynes 25	1	200-205	0.08	1.38	B21
Haynes C-276	1	165	0.39	6.98	B21

Table 2.2 (continued)
Summary of baseline fume generation data for arc welding electrodes

Electrode classification	Number of electrode brands evaluated	Current range, A (nominal)	Average range		Source table-App. B
			Fume generation rate, g/min	Weight of fumes/weight of deposited metal, g/kg**	
Aluminum					
ER4043	1	160-165	0.11-0.27	5.6-15.74	B22
ER5356	1	150-165	1.41-1.75(3.59)**	64.94-79.72(164.85)**	B23
Copper					
ERCu	1	205-210	0.30	4.93	B24
ERCu A1-A2	1	210-215	0.47	8.12	B24

*g/kg ÷ 10 = weight of fumes expressed as a percentage of the deposit weight.

**The data points in parentheses represent data obtained at non-baseline welding conditions (E6010 and ER5356) and with an E70T-4 electrode no longer in production.

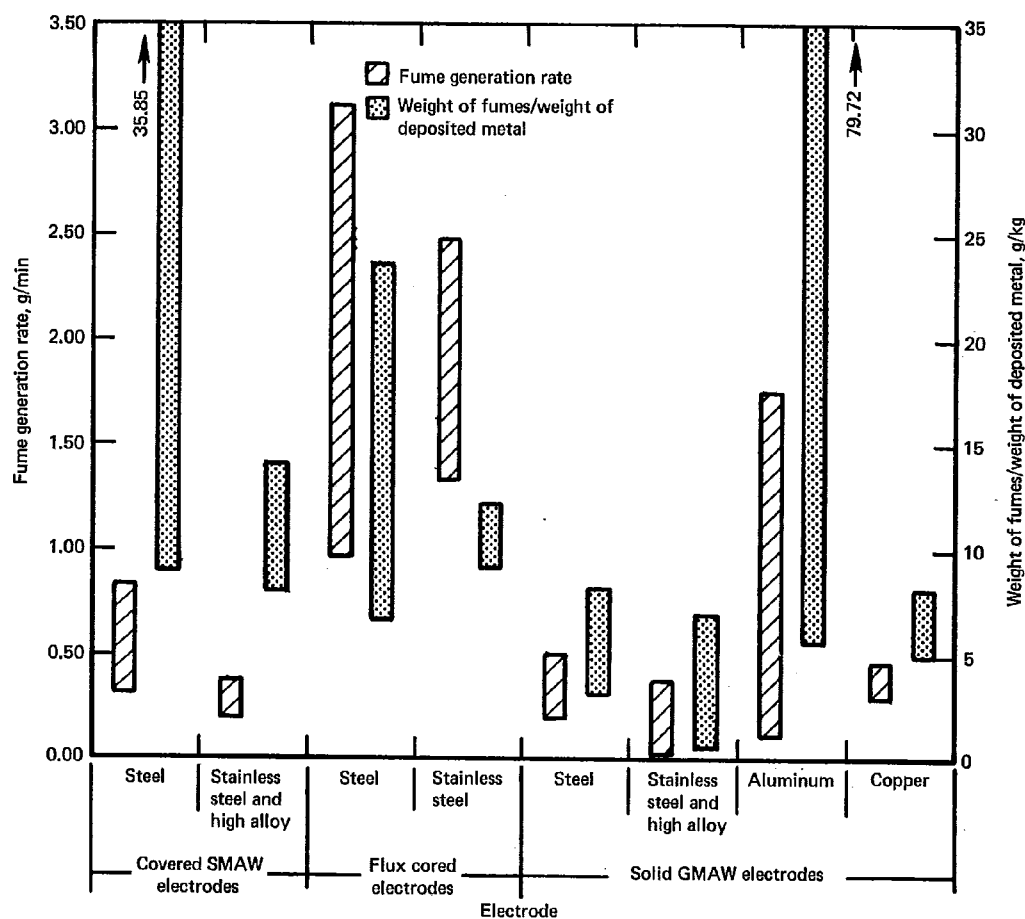


Fig. 2.5—Ranges of fume generation rates and ratios of weight of deposited metal for covered, flux cored, and solid GMAW electrodes

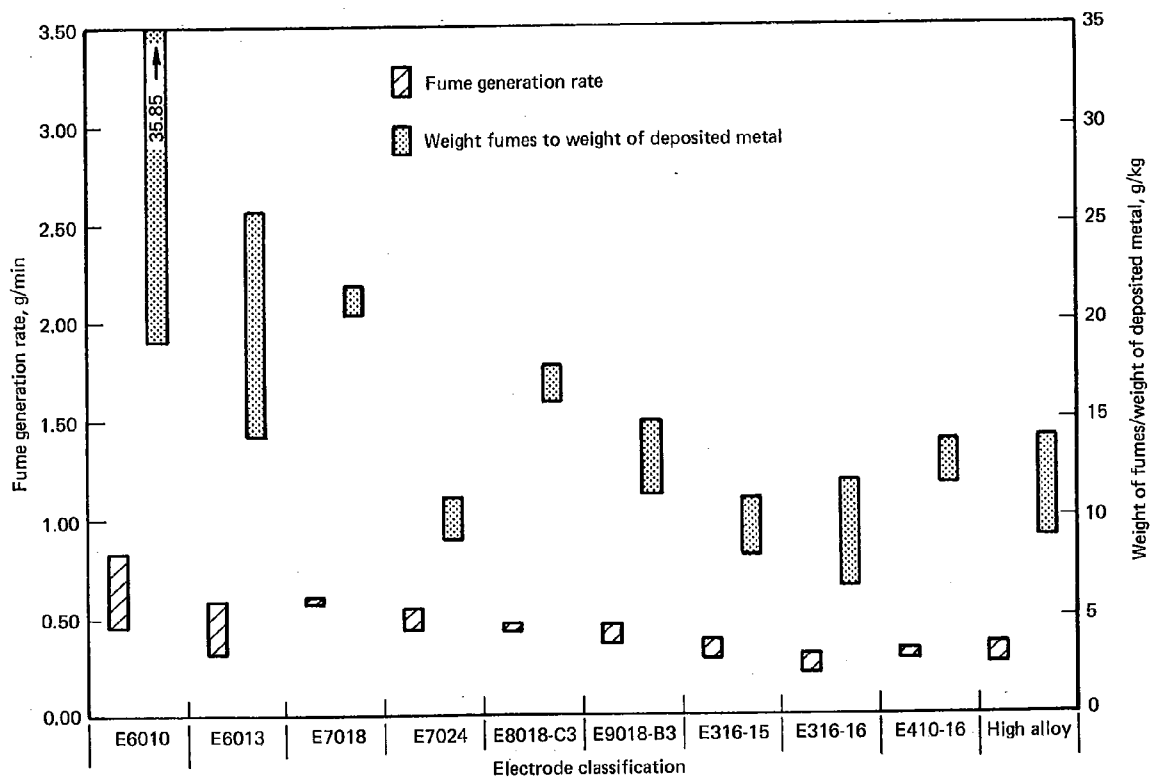


Fig. 2.6—Fume generation rates and ratios of weight of fumes to weight of deposited metal for covered electrodes

rates of the E7024 electrodes were comparable to those of other carbon and low alloy steel electrodes, even though the covering on these electrodes is much thicker than the coverings on the other electrodes. The ratios of weight of fume to weight of deposited metal for E7024 electrodes were lower than those of other electrodes. This results from the combination of a relatively low fume generation rate and the high deposition rate which results from the iron powder (up to 50 percent) in the coverings.

Fume generation rate ranges for stainless steel, nickel, and other high alloy covered electrodes were similar in magnitude; ranges for ratios of weight of fumes to weight of deposited metal generally overlapped one another.

Fume Composition. Studies to determine the complete analysis of the fumes associated with covered (and other types of) electrodes are not common; they can be quite involved and costly and may be unnecessary. Since the composition of the core wire is generally a matter of record, core wire constituents in the fumes can be readily determined by optical emission spectroscopy or atomic absorption procedures. Fume constituents attributable to the electrode coverings are more difficult to determine

and a combination of analytical methods may be needed. Optical emission spectroscopy provides a means for identifying most of the constituents in the fumes, since the presence of 70 or more elements can be detected on a semiquantitative base. This method should be supplemented by (a) atomic absorption analysis for more accurately determining elements present in large amounts and (b) wet chemical analysis for determining fluoride contents. X-ray diffraction is useful if there is interest in detecting compounds in the fumes. Such detailed analyses are seldom required; industry is generally concerned only with those fume constituents that have low threshold limit values or are present in large amounts.

Since a large number of electrodes were to be evaluated during this program, the AWS Research Committee agreed that analytical efforts would be limited to the detection of the major elements in the fumes (e.g., iron, manganese, and silicon for carbon steel electrodes) and fluorides. Atomic absorption analysis was used to detect selected elements because the equipment is readily available in industry, is reasonable in cost, and produces accurate results. Wet chemistry was used to detect fluorides. Data on the core wire elements in the fumes

produced by covered (and other) electrodes are presented later in this report (Table 2.21). It is noted that the analytical data do not total 100 percent because these limited studies did not include detection of fume constituents originating from the electrode covering.

Some data on expected fume constituents attributable to the coverings on the electrodes can be obtained from the literature. Compositions of the coverings of representative E6010 (high cellulose-sodium), E6013 (high titania-potassium), and E7016 (low hydrogen-potassium) electrodes have been provided by Smith and Rinehart (Ref. 2.18) and Smith (Ref. 2.19) and are shown in Table 2.3. The E6010 and E6013 electrodes are among the electrodes evaluated during this investigation. E7018 electrodes evaluated during the present program have coverings similar to that of the E7016 electrode except for the presence of iron powder in the E7018 covering. The fumes produced by the electrodes included in Table 2.3 should contain the constituents of the covering and those of the core wire, usually (but not necessarily) in the oxide form of the respective elements.

Examples of complete fume analyses of several Scandinavian electrodes, three of which appear to be low hydrogen electrodes with iron powder additions, are shown in Table 2.4.

Table 2.3
Composition of coverings on representative carbon steel electrodes (Refs. 2.18, 2.19)

Constituent	Covering composition, weight %		
	E6010	E6013	E7016
SiO ₂	32.0	25.9	16.0
TiO ₂ + ZrO ₂	18.0	30.6	6.5
Al ₂ O ₃	2.0	5.9	1.0
CaF ₂	---	---	27.0
CaO	---	1.6	---
MgO	6.0	2.6	---
Na ₂ O	8.0	1.1	1.4
K ₂ O	---	6.7	1.0
CO ₂	---	1.7	---
Organics	30.0	17.7	---
Fe	2.0	2.1	---
Mn	7.0	4.8	2.5
CaCO ₃	---	---	38.0

Table 2.4
Composition of fumes produced by typical Scandinavian covered electrodes (Ref. 220)

Compound	Composition, weight %			
	Electrode 1	Electrode 2	Electrode 3	Electrode 4
SiO ₂	7.0	9.5	10.0	30.5
Fe ₂ O ₃	25.5	24.5	36.5	43.5
Al ₂ O ₃	0.6	0.2	<0.1	<0.1
TiO ₂	1.1	0.2	0.5	2.2
ZrO ₂	---	0.6	---	---
MnO	4.7	7.2	8.2	9.8
ZnO	0.04	0.07	0.09	0.02
CaO	15.9	5.3	0.4	<0.1
MgO	0.1	0.1	1.0	0.1
K ₂ O	24.4	17.6	17.6	7.2
Na ₂ O	2.4	17.2	11.0	5.4
Cu	0.03	0.07	0.03	0.06
Pb	0.02	0.02	0.04	0.05
Cr	0.01	0.04	0.01	0.04
Fe	19.8	15.7	17.1	---

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In the AWS studies to characterize fumes and fume particles, optical emission spectroscopy was used to determine the constituents in the fumes produced by E7024 and E410-16 covered electrodes. Data on major constituents are shown in Table 2.5.

Flux Cored Electrodes

Fume Generation Characteristics. Ranges of (a) fume generation rates and (b) ratios of weight of fumes to weight of deposited metal for representative carbon steel, low alloy steel, and stainless steel flux cored electrodes are shown in Fig. 2.7. All electrodes were 2.4 mm (3/32 in.) diameter and welding was done at currents in the mid-portion of the manufacturer's recommended operating range. Details on the welding conditions and the experimental results are contained in Tables B11 and B15. Carbon dioxide shielding was used with the E70T-1, E70T-5, 81-C3, and 91-B3 electrodes; the E70T-4 and stainless steel electrodes were self-shielding. The data upon which Fig. 2.7 is based are summarized in Table 2.2; this table should be consulted when this figure is reviewed.

(1) E70T-1 electrodes. The ranges of fume generation and ratios of weight of fumes to weight of deposited metal were broadest for this classification of electrodes. Three of these electrodes were made by the same producer; the other two were made by two different producers. The electrodes made by the same producer were designed for single- or multiple-pass welding, but the core wire and flux composition varied to achieve certain

objectives: e.g., the welding of steel with different strength levels, the welding of clean or rusted steel, etc. These special-purpose electrodes defined the upper and lower limits of the ranges in Fig. 2.7. The electrode with the highest fume generation rate contained appreciable amounts of fluorides (Table 2.18); such compounds are known to enhance the production of fumes. The fluoride content of the fumes associated with the electrode having the lowest fume generation rate was very small.

(2) E70T-4 electrodes. A data point outside the indicated ranges for these electrodes is shown in Fig. 2.7. This point represents the fume generation rate for an E70T-4 electrode that was made several years ago and is no longer available on the market. Since another currently available electrode made by the same producer had a much lower fume generation rate, it appears that changes in the flux were made to reduce fume quantities.

(3) E70T-5 electrodes. The highest fume generation rates were encountered with E70T-5 electrodes. This was expected because the E70T-5 electrodes can be used with or without a shielding gas, and the basic type flux contains ingredients that produce large amounts of gas and fumes. Ratios of fume weight to weight of deposited metal were highest for these electrodes also.

Ranges for the fume generation characteristics of other flux cored electrodes overlapped one another in many instances. The experimental results are discussed below.

(1) Low alloy steel electrodes. The fume generation

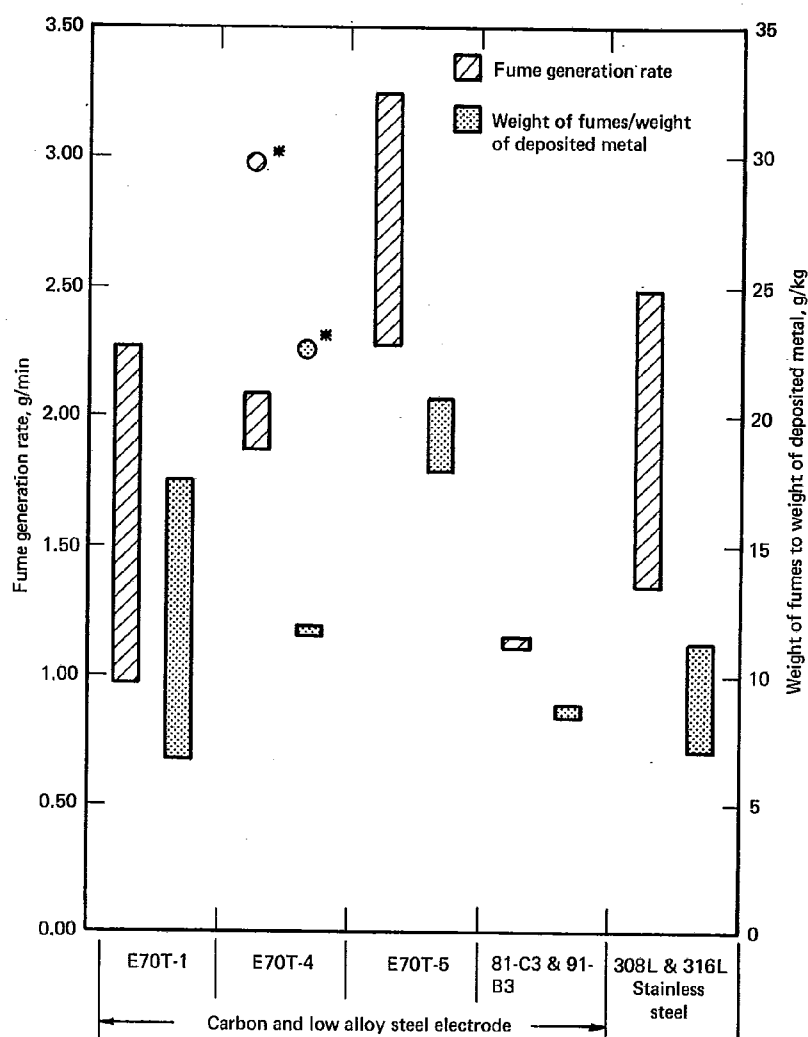
Table 2.5
Optical emission spectroscopic analysis of fumes produced by
two E7024 and one E410-16 covered electrodes

Element	(Oxide) ¹	Composition, weight %		
		E7024(7) ²	E7024(8) ²	E410-16(21) ²
Fe	(Fe ₂ O ₃)	20-30 (28.6-42.9)	20-30 (28.6-42.9)	10-20 (14.3-28.6)
Si	(SiO ₂)	10-20 (15.7-31.4)	5-10 (7.8-15.7)	2-3 (3.1-4.6)
K	(K ₂ O)	8-12 (9.6-14.4)	8-12 (9.6-14.4)	10-20 (12.0-24.0)
Na	(Na ₂ O)	3-6 (4.0-8.1)	3-6 (4.0-8.1)	4-8 (5.4-10.8)
Mn	(MnO ₂)	2-4 (3.2-6.3)	2-4 (3.2-6.3)	1-2 (1.6-3.2)
Ca	(CaO)	0.1 (0.1)	0.05 (0.1)	2-4 (2.8-5.6)
Zn	(ZnO)	<0.1 (0.1)	<0.1 (0.1)	0.1 (0.1)
Ti	(TiO ₂)	0.5 (0.8)	0.3 (0.5)	0.4 (0.7)
Al	(Al ₂ O ₃)	0.1 (0.2)	0.05 (0.1)	0.5 (0.9)
Cr		0.01	0.01	5-10

1. Assuming that elements are completely converted to oxides.

2. The number in parentheses following the electrode designation is the code number identifying the specific electrode.

Section IIB. Fume Generation Characteristics[79]



*Data from E70T-4 electrode that is no longer commercially available.

Fig. 2.7—Fume generation rates and ratios of weight of fumes to weight of deposited metal for flux cored electrodes

rates and ratios of weight of fumes to weight of deposited metal for 81-C3 and 91-B3 low alloy steel electrodes were low in comparison with those for carbon steel flux cored electrodes. These results are similar to those observed when these quantities were compared for carbon steel and low alloy steel covered electrodes.

(2) Stainless steel electrodes. The fume generation characteristics of the three self-shielded stainless steel electrodes investigated during this program varied over a wide range. This appears to be a flux-related occurrence. The E308LT-3 electrode and one of the E316LT-3 electrodes were made by the same producer, while the

remaining E316LT-3 electrode was made by another producer. The fume generation rates for the electrodes made by the same producer were similar and define the low end of the range shown in Fig. 2.7; this result might be expected because the fluxes used in these electrodes were probably quite similar in composition. However, the fume generation rates and ratios of weight of fumes to weight of deposited metal varied widely for the E316LT-3 electrodes made by two producers. Since the sheath compositions are not likely to differ substantially, this variation must be associated with differences in the flux cores of the respective electrodes.

Table 2.6
Comparison of average fume generation characteristics of
2.4 mm (3/32 in.) diameter E70T-1 flux cored electrodes
as a function of shielding gas

Electrode number	Shielding gas ¹	Current, A	Fume generation rate, g/min.	Weight of fumes/weight of deposited metal, g/kg
E70T-1 (40) ²	CO ₂	475	1.35	10.40
E70T-1 (40)	Ar-25 CO ₂	465	1.01	7.78
E70T-1 (42)	CO ₂	440	2.27	17.51
E70T-1 (42)	Ar-25 CO ₂	445	1.93	14.91

1. Ar-25 CO₂ is a convention used to designate a gas mixture of 25% CO₂, 75% Ar.
2. The number in parentheses after the AWS electrode classification is a code number identifying the specific proprietary electrode.

Table 2.7
Typical flux compositions of the three carbon dioxide
shielded flux cored electrode types, percent (Ref. 2.17)

Compound or element	Composition, weight percent		
	Type 1 Titania type (non-basic) flux	Type 2 Lime-titania type (basic or neutral) flux	Type 3 Lime type (basic) flux
SiO ₂	21.0	17.8	7.5
Al ₂ O ₃	2.1	4.3	0.5
TiO ₂	40.5	9.8	---
ZrO ₂	---	6.2	---
CaO	0.7	9.7	3.2
Na ₂ O	1.6	1.9	---
K ₂ O	1.4	1.5	0.5
CO ₂ (as carbonate)	0.5	---	2.5
C	0.6	0.3	1.1
Fe	20.1	24.7	55.0
Mn	15.8	13.0	7.2
CaF ₂	---	18.0	20.5
AWS classification	E70T-1 or E70T-2	E70T-1	E70T-1 or E70T-5

As noted previously, the E70T-1 and E70T-5 electrodes were used with CO₂ shielding. To investigate the premise that fume generation rates can be affected by the type of shielding gas used during welding, the characteristics of two E70T-1 flux cored electrodes were determined with Ar-25 CO₂ shielding. Other than shielding gas, the welding conditions were essentially the same as the baseline conditions. The resulting data are summarized in Table 2.6; additional details are contained in Appendix B (Table B25).

The fume generation rates for each electrode were reduced between 15 and 25 percent when Ar-25 CO₂ shielding was used instead of CO₂. This is because the argon-based shielding gas has a lower oxidation potential than CO₂, and oxidation processes contributing to the formation of fumes at and near the tip of the electrode were decreased as a consequence. The metal deposition rates for these electrodes were unaffected by the type of gas shielding used. Thus, the ratios of weight of fumes to weight of deposited metal were also smaller when Ar-25 CO₂ was used for shielding.

Fume Composition. As in the case of covered electrodes, the composition of fumes produced by flux cored electrodes is determined by composition of the electrode sheath, flux core, and, to a minor extent, by the base metal. Since the composition of the sheath for electrodes within a classification is unlikely to vary much from producer to producer, variations in fume compositions for such electrodes are caused primarily by differences in the flux core ingredients.

To provide an insight into the constituents that may be detected in the fumes associated with welding operations, data on the composition of flux cores and slags associated with representative flux cored electrodes are shown in Tables 2.7 and 2.8 (Ref. 2.17). The compositions of the fluxes used in three CO₂ shielded flux cored electrodes are shown in Table 2.7. Electrodes incorporating these fluxes can be included in one or two AWS classifications; classification criteria are discussed in the article from which these data were taken (Ref. 2.17). The type of flux also determines the classification of self-shielded flux cored electrodes as indicated in Table 2.8.

Table 2.8
Typical flux compositions of the four types of self-shielded flux cored electrodes, percent (Ref. 2.17)

Compound or element	Composition, weight percent			
	Type 1 Fluorspar-aluminum flux	Type 2 Fluorspar-titania flux	Type 3 Fluorspar-lime-titania flux	Type 4 Fluorspar-lime flux
SiO ₂	0.5	3.6	4.2	6.9
Al	15.4	1.9	1.4	---
Al ₂ O ₃	---	---	---	0.6
TiO ₂	---	20.6	14.7	1.2
CaO	---	---	4.0	3.2
MgO	12.6	4.5	2.2	---
K ₂ O	0.4	0.6	---	---
Na ₂ O	0.2	0.1	---	0.6
C	1.2	0.6	0.6	0.3
CO ₂ (as carbonate)	0.4	0.6	2.1	1.3
Fe	4.0	50.0	50.5	58.0
Mn	3.0	4.5	2.0	7.9
Ni	---	---	2.4	---
CaF ₂	63.5	22.0	15.3	22.0
AWS classification	E70T-4 E60T-7 E60T-8	E70T-3	E70T-6	E70T-5

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Most of the flux constituents shown in these tables will be present as elements and compounds in the fumes produced by electrodes incorporating them. They will not be present in the same proportions as in the flux because some constituents are transferred by the arc to the slag and, in some cases, to the weld metal. Elemental compositions of the fumes produced by typical E70T-1, E70T-4, and E70T-5 electrodes are shown in Table 2.9 along with calculated oxide contents (assuming that the elements are converted to oxides (Ref. 2.3). These electrodes were classified as follows: E70T-1, rutile-base; E70T-4, fluorspar-base; and E70T-5, silica-base.

Fume compositions determined by optical emission spectroscopy are shown in Table 2.10 for the E70T-1, E70T-4, and E70T-5 electrodes investigated during this program. These data were acquired during studies to characterize fumes and fume particles. From these data, it appears that the E70T-4 electrodes evaluated by Battelle and by Heile and Hill had fluxes based on similar ingredients (e.g., aluminum and fluorspar). Fluxes for the respective E70T-1 and E70T-5 electrodes differed considerably.

Solid Electrodes

The fume generation characteristics of solid electrodes and rods used for gas metal arc welding and gas tungsten arc welding are reviewed in this section. In comparison with covered and flux cored electrodes, these are low fuming electrodes and rods whose fume generation tendencies are a direct function of the amount of electrode or rod consumed during welding. Other factors which influence the rate at which fumes are produced by the solid electrodes include the type of shielding gas, the metal transfer characteristics of the arc, and the welding conditions.

Gas Metal Arc Electrodes

Fume Generation Characteristics. Ranges for fume generation rates and ratios of weight of fume to weight of deposited metal associated with carbon steel, stainless steel, high alloy, copper, and aluminum gas metal arc welding electrodes investigated during this program are shown in Fig. 2.8. The data upon which these ranges are based are summarized in Table 2.2; detailed information on the fume generation characteristics of individual electrodes are contained in Tables B16 to B24 along with the welding conditions.

(1) **Steel Electrodes.** The results obtained with carbon steel electrodes are reviewed separately from those obtained with other types of solid electrodes. Caution is required in interpreting the data in Fig. 2.8 because of the dependency of the fume generation characteristics on welding current and other process variables. The fume generation characteristics of three 1.1 mm (0.045 in.) E70S-3 electrodes, each made by a different manufacturer, were determined at appropriate current levels in the following transfer modes: spray transfer with Ar-2 O₂ or Ar-9 CO₂ shielding; globular transfer with CO₂ shielding; and short circuiting transfer with Ar-25 CO₂ shielding. Although the electrodes were made by different producers, there was little variation in composition. The thickness of the copper coating on the electrode surface varied from zero to several microinches. A single E70S-5 electrode was also evaluated in various transfer modes: spray transfer with Ar-2 O₂ shielding; globular transfer with CO₂ shielding; and short circuiting transfer with Ar-25 CO₂ shielding.

Fume generation rates for the three E70S-3 electrodes were similar in magnitude during spray transfer welding with Ar-2 O₂ or Ar-9 CO₂ shielding, and during globular transfer welding with CO₂ shielding. Under these conditions, the ratios of weight of fumes to weight of deposited metal varied somewhat because of differ-

Table 2.9
Composition of fumes from flux cored arc welding (Ref. 2.3)

Element	(Oxide)	Composition, weight percent		
		E70T-1	E70T-4	E70T-5
Fe	(Fe ₂ O ₃)	28 (40.0)	13 (18.6)	23 (32.9)
Mn	(MnO ₂)	5 (7.9)	2 (3.2)	4 (6.3)
Si	(SiO ₂)	25 (39.3)	4 (6.3)	20 (31.4)
Ca	(CaO)	---	13 (18.2)	8 (11.2)
Ti	(TiO ₂)	2 (3.3)	---	---
Mg	(MgO)	3 (5.0)	9 (14.9)	---
Al	(Al ₂ O ₃)	---	9 (17.0)	---
F		7	13	7

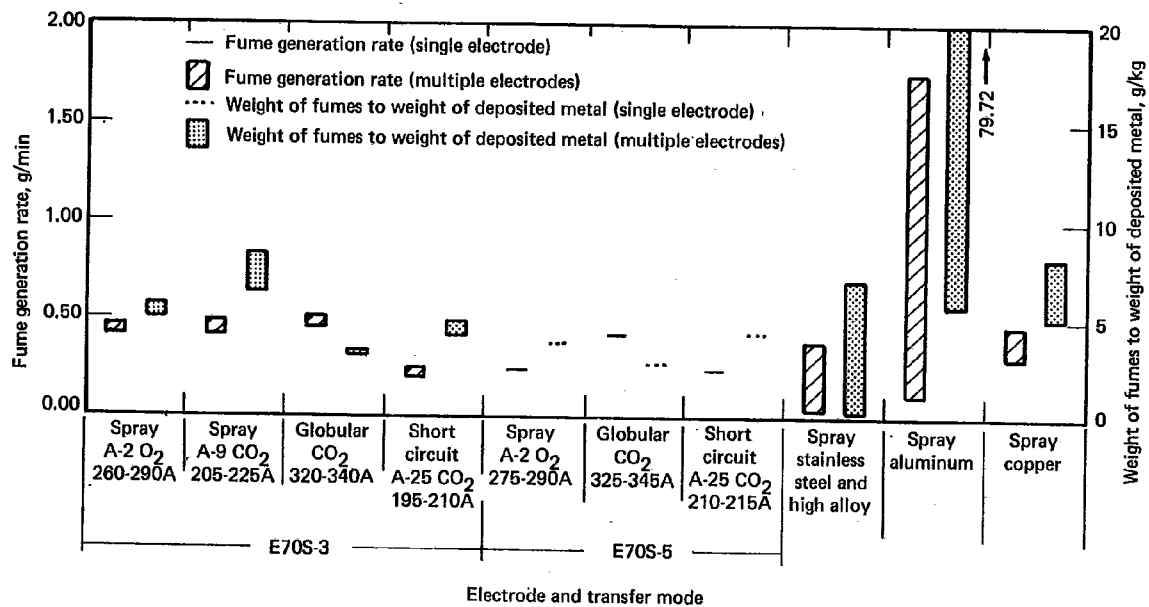


Fig. 2.8—Fume generation rates and ratios of weight of fumes to weight of deposition metal for gas metal arc electrodes

Table 2.10
Optical emission spectroscopic analysis of fumes produced by
E70T-1, E70T-4, and E70T-5 flux cored electrodes

Element	(Oxide) ¹	Composition, weight %					
		E70T-1 (42) ²		E70T-4 (49) ²		E70T-5 (50) ²	
Fe	(Fe ₂ O ₃)	30-40	(42.9-57.2)	15-25	(21.4-35.8)	30-40	(42.9-57.2)
Si	(SiO ₂)	2-3	(3.1-4.6)	0.1	(0.2)	2-3	(3.1-4.6)
K	(K ₂ O)	1.0	(1.2)	2.0	(2.4)	4-6	(4.8-7.2)
Na	(Na ₂ O)	4-6	(5.4-8.1)	0.1	(0.1)	1.0	(1.4)
Mn	(MnO ₂)	4-6	(6.3-9.5)	2-3	(3.2-4.7)	4-6	(6.3-9.5)
Ca	(CaO)	0.1	(0.1)	15-25	(21-35)	8-12	(11.2-16.8)
Zn	(ZnO)	0.1	(0.1)	0.1	(0.1)	0.1	(0.1)
Ti	(TiO ₂)	0.5	(0.8)	0.01	(0.02)	0.2	(0.3)
Al	(Al ₂ O ₃)	0.4	(0.8)	7-10	(13.2-18.9)	1-2	(1.9-3.8)
Mg	(MgO)	0.02	(0.03)	7-10	(11.6-16.6)	0.2	(0.3)

1. Assuming that elements are completely converted to oxides.

2. The number in parentheses following the electrode designation is the code number identifying the specific electrode.

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ences in the metal deposition rates for the respective electrodes. Under short circuiting conditions with Ar-25 CO₂ shielding, fume generation rates were lower than they were with other metal transfer modes and other shielding gases.

The effects of type of shielding gas and mode of metal transfer on fume generation characteristics are not clearly evident from the data in Fig. 2.8 or the tabular data mainly because of the differences in the currents used for welding. If the effects of current are taken into account by normalizing⁷ the data to a selected value of current (multiplying the normalized fume generation rate for each electrode by current squared), the effects of shielding gas and metal transfer mode are more readily observed. To facilitate interpreting the data, the average fume generation rates were normalized to a current of 250 A. These data together with the measured rates are shown in Table 2.11.

As indicated in Table 2.11, fumes were produced at the highest rate during spray transfer welding with Ar-9 CO₂ shielding, followed approximately in descending

order by spray transfer welding with Ar-2 O₂, short circuiting transfer welding with Ar-25 CO₂, and globular transfer welding with CO₂. The effects of shielding gas on fume generation rates can be best observed by comparing the rates at which fumes were produced during spray transfer welding with Ar-2 O₂ or Ar-9 CO₂ shielding. When Ar-9 CO₂ was used, the fume generation was much higher than when Ar-2 O₂ shielding was used. This reflects the higher oxidation potential of the Ar-9 CO₂ shielding gas, and the fume generation rate presumably would increase further if the content of CO₂ in the argon-based shielding gas was increased.

The E70S-5 electrode is similar to the E70S-3 electrode except that it contains aluminum as well as manganese and silicon as a deoxidizer. If the same welding conditions are used, the fume generation characteristics of the E70S-3 and E70S-5 electrodes should be similar, as indeed they were (see Tables B16 through B19).

(2) Other Solid Electrodes. Representative stainless steel, high alloy, copper, and aluminum solid electrodes, 1.1 mm (0.045 in.) in diameter,⁸ were also investigated. In each instance, a single electrode per classification was evaluated and the welding current was adjusted to produce acceptable spray transfer conditions.

(3) High Alloy Electrodes. Five high alloy electrodes (one stainless steel electrode, three nickel base electrodes, and one cobalt-base electrode) were investigated during this program, and all but one had fume generation rates and ratios of weight of fumes to weight of deposited metal well below those of carbon steel electrodes. This trend was also observed with covered electrodes of the same types. The exception, a nickel-base electrode, had fume generation rates approaching

7. In general, fume generation rates for electrodes studied in this and other investigations varied in accordance with current to a power that ranged from greater than one to less than three (current equals I^x where $1 < x < 3$). With current squared accepted as a reasonable power function compromise, a normalized fume generation rate that includes the effect of current on the rate at which fumes are produced can be established. Then, if an electrode is used at one current, it is possible to use the normalized rate (fume generation rate per unit of current squared) and predict the approximate fume generation rate when the electrode is used at a higher or lower rate (provided other welding variables are controlled). Normalized fume generation rates are shown in the tabular data in Appendix B along with measured rates.

8. Because of availability, electrodes with diameters other than 0.045 in. (1.1 mm) were used in a few instances; such deviations are noted in the tabular data in Appendix B.

Table 2.11
Measured and normalized (Ref. 2.1) fume generation rates for E70S-3 electrodes

Metal transfer mode	Shielding gas	Fume generation rate g/min					
		E70S-3(54) ²		E70S-3(57) ²		E70S-3(58) ²	
		Measured	Normalized	Measured	Normalized	Measured	Normalized
Spray	Ar-2 O ₂	0.41	0.35	0.46	0.36	0.45	0.35
Spray	Ar-9 CO ₂	0.41	0.58	0.44	0.62	0.49	0.61
Globular	CO ₂	0.51	0.29	0.46	0.28	0.45	0.27
Short circuit	Ar-25 CO ₂	0.20	0.33	0.25	0.38	0.24	0.38

1. Fume generation rates normalized to a current of 250 A.

2. The number in parentheses following the electrode designation is the code number identifying the specific electrode.

those of the carbon steel electrodes. It was a small diameter electrode, 0.09 mm (0.035 in.), and the current density was higher than that used with the other electrodes; as a result, arc temperatures were probably higher and more fumes were produced.

(4) Aluminum Electrodes. The aluminum electrodes presented mixed results. The ER4043 electrode produced fumes at low rates and the ratio of weight of fumes to weight of deposited metal was low also. The ER5356 electrode produced fumes at much higher rates than the ER4043 electrode. High fume generation rates were not unexpected, because the ER5356 electrode contains magnesium, a metal that oxidizes easily and has a high vapor pressure. In contrast, the ER4043 electrode contains silicon, an element with a much lower vapor pressure. Using a contact tube-to-work distance of 12.5 mm (0.50 in.), the fume generation rate for the ER5356 electrode was similar to that obtained by Heile and Hill when differences in welding current are taken into account (Ref. 2.3). Much higher fume generation rates were produced at longer contact tube-to-work distances, and there was evidence of lack of shielding of the arc and pool of weld metal. These results point to the need for careful welding torch setup control and good shielding to minimize fumes as well as to insure the production of high quality welded joints.

(5) Copper Electrodes. Fume generation rates and ratios of weight of fumes to weight of deposited metal for an ERCu and an ERCuAl-A2 electrode were comparable in magnitude to those associated with carbon steel electrodes.

Fume Compositions of Gas Metal Arc Electrodes. In contrast to covered and flux cored electrodes, the composition of the fumes produced by gas metal arc welding electrodes is controlled by the composition of the electrode and any coating that might be on the electrode surface. This can be illustrated by considering the composition of the fumes produced by the three E70S-3 electrodes investigated during this study:

Electrode no.	Fume composition, weight percent					
	Fe	(Fe ₂ O ₃)	Mn	(MnO ₂)	Si	(SiO ₂) Cu
E70S-3 (54)	63.7	(91.1)	5.3	(8.4)	0.05	(0.1) 0.11
E70S-3 (57)	65.7	(93.9)	3.8	(6.0)	0.79	(1.2) 0.60
E70S-3 (58)	62.5	(89.4)	8.5	(13.4)	0.53	(0.8) 1.00

Each of the fume samples contained iron, manganese, silicon, and copper (or their oxides). The amount of copper in the fumes produced by the electrode that was not coated with copper, E70S-3 (54), was higher than expected. Subsequent analyses of short lengths of each electrode from which the copper coating was stripped showed that they all contained a small (0.02 to 0.03) weight percent of copper as a residual element in the electrodes themselves. Apparently, the residual copper in the E70S-3 (54) electrode plus perhaps some copper picked up from contact tube and wire drive was the source of copper in the fumes from this electrode.

Because of its low threshold limit value, there is more concern about the presence of copper fume in the welding environment than about iron oxide fume. Table 2.12 combines data on the baseline fume generation rates of three E70S-3 electrodes with the compositional data on

Table 2.12
Results of studies on copper in the fumes produced by
E70S-3 electrodes used for gas metal arc welding

Characteristic	Electrode		
	E70S-3(54)*	E70S-3(57)	E70S-3(58)
Copper coating on electrode			
Thickness, μ in.	0	18	24
weight percent	0	0.19	0.24
Copper content of fumes, weight %	0.11	0.60	1.00
Iron (oxide) content of fumes, weight %	63.7 (91.1)	65.7 (93.9)	62.5 (89.4)
Total fume generation rate, g/min.	0.41	0.46	0.45
Copper fume generation rate, g/min.	0.0004	0.0028	0.0045
Iron (oxide) fume generation rate, g/min.	0.26 (0.37)	0.30 (0.43)	0.28 (0.40)

*The number in parentheses following the electrode designation is a code number identifying the specific electrode.

the fumes. The ACGIH time-weighted average threshold limit value for iron oxide fumes (5 mg/m^3) is 25 times as large as that for copper fumes (0.2 mg/m^3). However, the results of the experimental studies indicate that the iron oxide fume generation rates for the E70S-3 (54), E70S-3 (57), and E70S-3 (58) electrodes were 925, 154, and 89 times as great, respectively, as the copper fume generation rates. Thus, when welding with these electrodes, the allowable limit for iron oxide fumes would be exceeded long before reaching the limit for copper fumes.

Compositions of the fumes produced by the gas metal arc electrodes used for welding other base metals (stainless steels, nickel base alloys, etc.) are determined by the composition of the respective electrodes.

Gas Tungsten Arc Welding

Fume Generation Characteristics. Two filler rods used for gas tungsten arc welding were also evaluated: a 3.2 mm (1/8 in.) diameter E308L stainless steel wire and a 2.4 mm (3/32 in.) diameter 5356 aluminum alloy wire. The welding conditions are indicated below:

308L Stainless Steel Filler Metal. Welding was done with a torch equipped with a 2.4 mm (3/32 in.) diameter 2 percent thoriated tungsten electrode (AWS EWTh-2). The welding current was 200-215 A (dc), the electrode polarity was negative, and argon was used for shielding.

5356 Aluminum Filler Metal. Welding was done with a torch equipped with a 2.4 mm (3/32 in.) diameter tungsten electrode (AWS EWP). The welding current was 250 A (ac) and argon was used for shielding.

Under these conditions, the fume generation rates were 0.0025 and 0.0065 g/min for the stainless steel and aluminum filler wires, respectively. Such rates are a small fraction of the rates associated with other processes investigated during this program.

Fume Compositions. No analyses were made.

Section IIC. Effects of Process Variables on Fume Generation Rates

While baseline data on the fume generation characteristics of covered, flux cored, and solid electrodes provide a wealth of information that is useful to those concerned with the health and safety of welding personnel, they are by no means the entire story. The term "baseline" itself implies that these data were obtained when the electrodes were used in general accordance with recommended conditions, and questions concerning the effects of the process variables on fume generation characteristics naturally arise. In reviewing the baseline data, reference to the effect of current on these characteristics has been frequently made because it appears to be the dominant variable. Other welding variables also have a bearing on the

rate at which fumes are produced during welding. Some of the other variables affecting fume production are:

- (1) Voltage
- (2) Electrode polarity
- (3) Shielding gas (flux cored and solid electrodes)
- (4) Contact tube-to-work distance (flux cored and solid electrodes)
- (5) Metal transfer mode
- (6) Electrode characteristics (manufacturer, diameter, core wire composition, covering or flux composition, etc.).

All of these variables in addition to current and their effects on fume generation characteristics will be discussed in this section. It should be noted that the effects of many of these variables are interrelated.

Current Effects

Current is acknowledged to have a major effect on the rate at which fumes are produced during welding. In the present investigation, current effects were studied with representative covered, flux cored, and solid electrodes used for welding carbon steels. Trends similar to those observed should be obtained with other classifications of electrodes.

Covered Electrodes. Fume generation rate as a function of current is shown in Fig. 2.9 for 4 mm (5/32 in.) E6010 and E7018 electrodes; the data forming the basis for this figure are contained in Tables B26 and B27. In each instance, these rates varied nonlinearly with current. Studies to fit the data to a power function indicated that the fume generation rate (FGR) relation to current was different for each type of electrode. For example, the regression equations for two of the electrodes were

$$FGR_{E6010} = 0.000011 I^{2.24} \text{ with } r^2 = 0.93$$

$$FGR_{E7018} = 0.00017 I^{1.54} \text{ with } r^2 = 0.88$$

The regression lines in the figure are I^2 lines included for comparison purposes.

The results obtained are similar to those obtained by other investigators. Kobayashi, Maki, and Ohe noted that fume generation rates for ilmenite, lime, and lime-titania covered electrodes varied with current to powers of 1.17 to 1.74 (Ref. 2.5). Agreement with their results was good considering differences between domestic and foreign electrodes and differences in fume sampling methods. In work done by Heile and Hill with E6010 and E7018 electrodes, similar trends in fume generation rates were observed (Ref. 2.3).

Flux Cored Electrodes. The effects of welding current on fume generation rates for a 2.31 mm (3/32 in.) diameter E70T-1 electrode using CO_2 shielding are also shown in Fig. 2.9; details on the welding conditions and the results of this investigation are provided in Table B28. Above 450 A, the fume generation rate increased almost linearly with current; below 450 A, the behavior of the fume generation rate with current was nonlinear. In particular, there was a well-defined and reproducible minimum at low current levels that may have been caused by

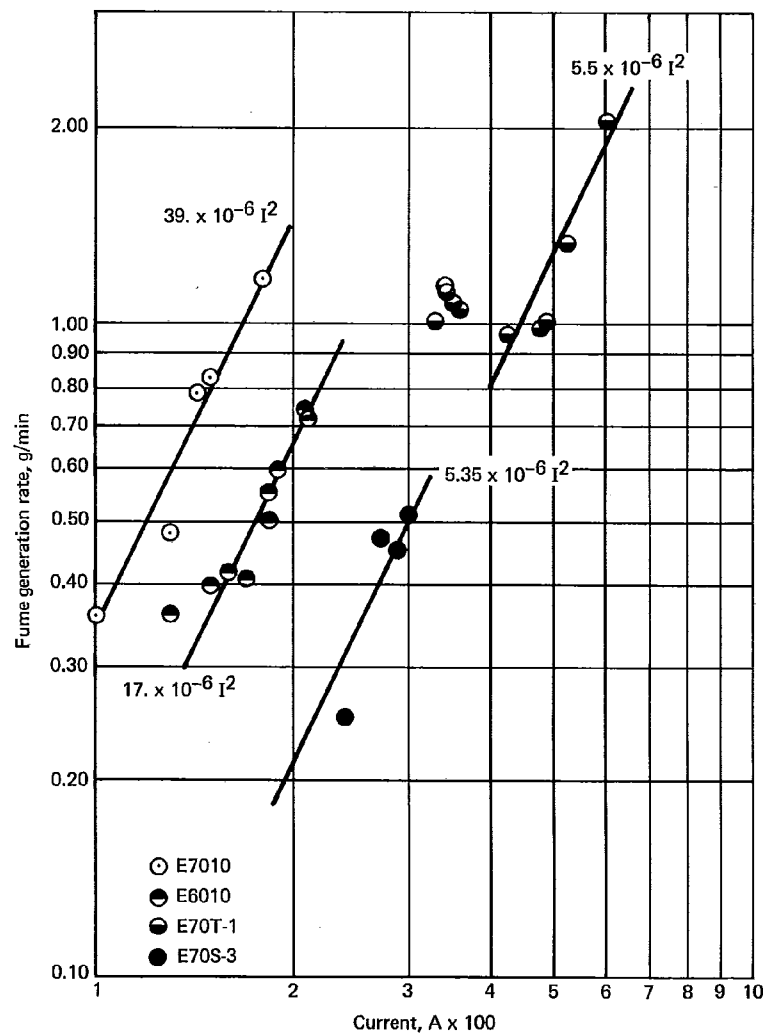


Fig. 2.9—Fume generation rates for selected covered, flux cored, and solid GMAW electrodes as a function of current

changes in arc length, changes in the sizes of globules being transferred across the arc, short-circuiting, etc. Attempts to fit a power function to the data obtained over the entire current range were unsuccessful because of the minimum in the curve at low currents. A reasonable fit with the I^2 line was obtained for data obtained at currents above 425 A. Thus, at currents between 425 and 600 A, there was a strong dependency of fume generation rate on current; at currents below 425 A, the fume generation rate was dependent upon variables other than current. It is emphasized that the indicated relationship between

fume generation rate and current is valid only for the data obtained during this study.

A video camera was used to study the arc at currents between 350 and 500 A. At currents around 500 A, the arc was steady and appeared to have a length of about 3.2 mm (1/8 in.). At currents in the 350 A range, the arc was turbulent and its length varied rapidly; at times, the arc was buried. Apparently, the minimum in the curve and the increase in fume generation rate at lower currents were associated with this turbulence and the changes in type of metal transfer.

Solid GMAW Electrodes. The effect of current on the fume generation rates for a 1.1 mm (0.045 in.) diameter E70S-3 electrode is shown in Fig. 2.9. The shielding gas was Ar-2 O₂, and welding was done in the spray transfer range to avoid introducing variations in data associated with the change from globular to spray transfer. The welding conditions and experimental data are contained in Table C29.

As indicated in Fig. 2.9, the fume generation rate increased gradually with current over the range investigated. Lower fume generation rates in this range were observed by Heile and Hill (Ref. 2.3). Such differences could be associated with a lower voltage (shorter arc length), shorter contact tube-to-work distance, better shielding, etc. Their current range extended downward to 100 A and a minimum in the fume generation rate was observed where the transfer mode changed from spray to globular.

Covered Electrode Welding at High Currents. Studies were undertaken to determine if the fume generation characteristics of covered electrodes were similar in magnitude to those obtained with flux cored electrodes when welding was done at comparable current levels. Two 6.4 mm (1/4 in.) diameter electrodes were included in this investigation: a low hydrogen, iron powder electrode (E7018) with a recommended operating range of 300 to 350 A, and a high titania, iron powder electrode (E7024) with a recommended operating range of 385 to 400 A. The resulting data are contained in Table B40.

Table 2.13 was prepared to facilitate comparison of the characteristics of these electrodes with those flux

cored electrodes. The fume generation rates for the E7018 and E7024 electrodes at high welding currents were similar in magnitude to those of the flux cored electrodes. Only one electrode, E70T-5(50), had a substantially higher fume generation rate than either of the covered electrodes. The ratio of weight of fumes to weight of deposited metal was higher for the E7018 electrode than for any of the flux cored electrodes. This reflects the relatively low metal deposition rate of the E7018 electrode in comparison to those of the flux cored electrodes. For an electrode with a much higher deposition rate, E7024, this ratio was similar to those of several flux cored electrodes. The results indicate that the fume generation rates for covered and flux cored electrodes are similar when the electrodes are used at similar current levels.

Current Density Effects

Since current density also has a bearing on the rate at which fumes are produced, this variable was studied to obtain a better understanding of its effects when welding was done with electrodes having different diameters.

Variable Current Density. The fume generation characteristics of three electrodes with diameters of 3.2 mm (1/8 in.), 4 mm (5/32 in.), and 4.8 mm (3/16 in.) were investigated; all electrodes were made by the same producer. Welding with all electrodes was done at a nominal current of 150 A; both direct current (electrode positive) and direct current (electrode negative) were used. Under these conditions, the approximate current densities were as follows: 12 200 A/in.² (1890 A/cm²) for the 1/8 in.

Table 2.13
Comparison of fume generation characteristics of covered and flux cored electrodes obtained at comparable current levels

Electrode (no.)	Current, A	Fume generation rate		Weight of fumes/ weight of deposited metal, g/kg*
		Measured, g/min	Normalized, μg/min/l ²	
Covered electrodes				
E7018 (72)	390-400	1.60	10.3	27.91
E7024 (73)	385-395	2.13	14.0	19.28
Flux cored electrodes				
E70T-1 (40)	470-485	1.36	5.8	10.40
E70T-4 (41)	455-465	0.96	4.5	6.65
E70T-4 (42)	435-445	2.27	11.5	17.51
E70T-1 (46)	435-445	1.33	6.9	9.97
E70T-1 (47)	435	1.83	9.7	14.17
E70T-4 (56)	370-390	1.86	12.5	12.76
E70T-4 (49)	400-410	2.09	12.9	13.83
E70T-5 (44)	425-445	2.26	11.8	17.87
E70T-5 (50)	440-450	3.25	16.6	23.63

*g/kg ÷ 10 = weight of fumes expressed as a percentage of deposit weight

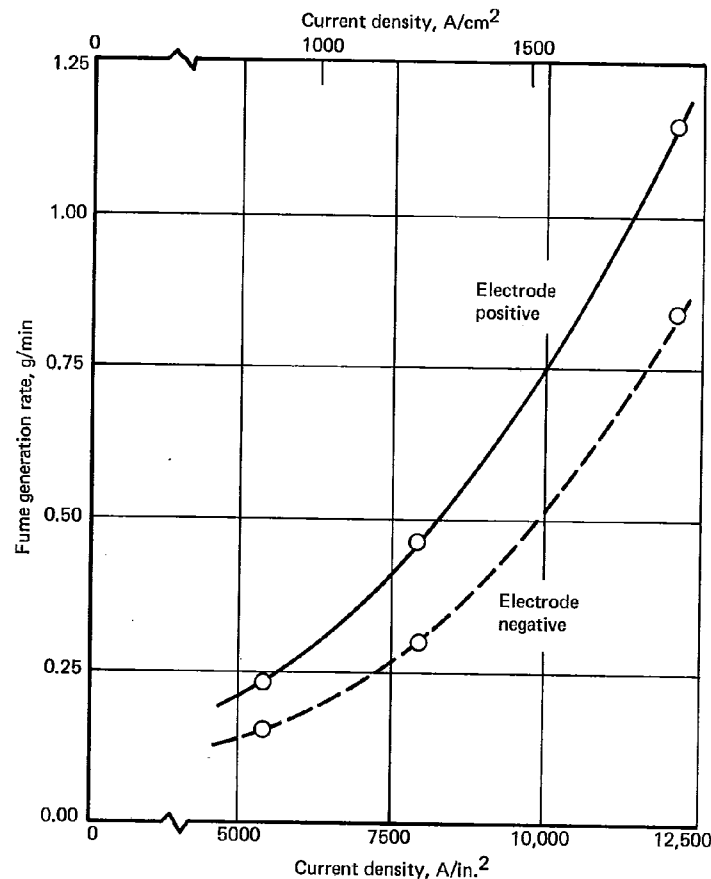


Fig. 2.10—Fume generation rates for E7018 covered electrodes with different diameters as a function of current density and electrode polarity

diameter electrode; 7800 A/in.² (1210 A/cm²) for the 5/32 in. diameter electrode; and 5400 A/in.² (840 A/cm²) for the 3/16 in. diameter electrode. Note that there are non-ideal operating conditions, since the current density for the 1/8 in. diameter electrode is high and the current density for the 3/16 in. diameter electrode is low. However, the conditions used were useful in studying current density effects. The results of this investigation are shown in Fig. 2.10; experimental details appear in Tables B30 and B31.

In Fig. 2.10, the fume generation rate increased with current density in what appears to be a parabolic relationship. The current density was highest in the 1/8 in. diameter electrode. As a result, the arc temperature was higher than that for larger electrodes and a resultant higher fume generation rate was observed. When direct current (electrode positive) was used, the fume generation rate was higher than that observed when direct

current (electrode negative) was used. This occurred because the electrode is heated to higher temperatures when the anode spot is on the electrode.

Constant Current Density. The fume generation characteristics of four E7018 electrodes with diameters ranging from 2.4 mm (3/32 in.) to 4.8 mm (3/16 in.) were studied to determine the effects of constant current density. The welding currents were selected to produce current densities of approximately 8000 to 8500 amperes per square inch. The resulting data are shown in Fig. 2.11 and 2.12 and in Table B32. With these welding conditions, the fume generation rate varied approximately with the square of electrode diameter (Fig. 2.11). The electrode melting rate was also approximately proportional to the square of the diameter (Table B32). The tabular data indicate that the amount of fumes produced during welding was largely dependent upon the amount of electrode consumed. Figure 2.12 shows the dependence

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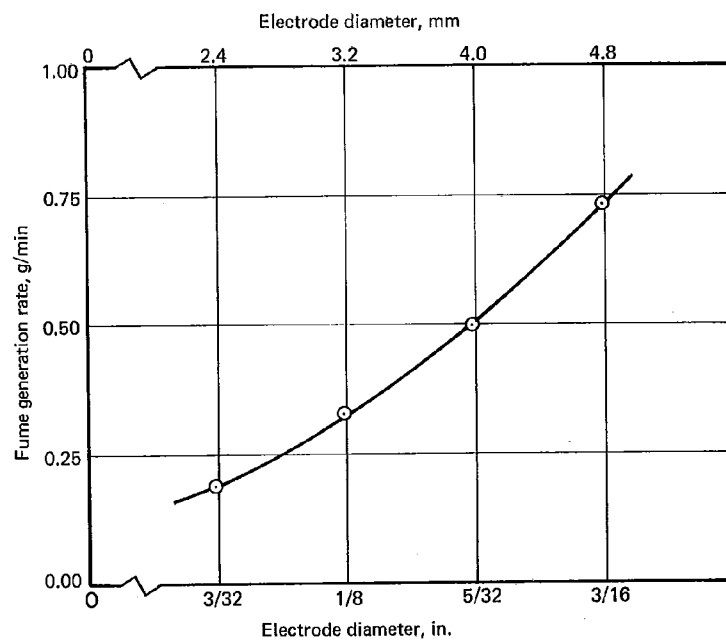


Fig. 2.11—Fume generation rates for E7018 covered electrodes with different diameters at constant current densities

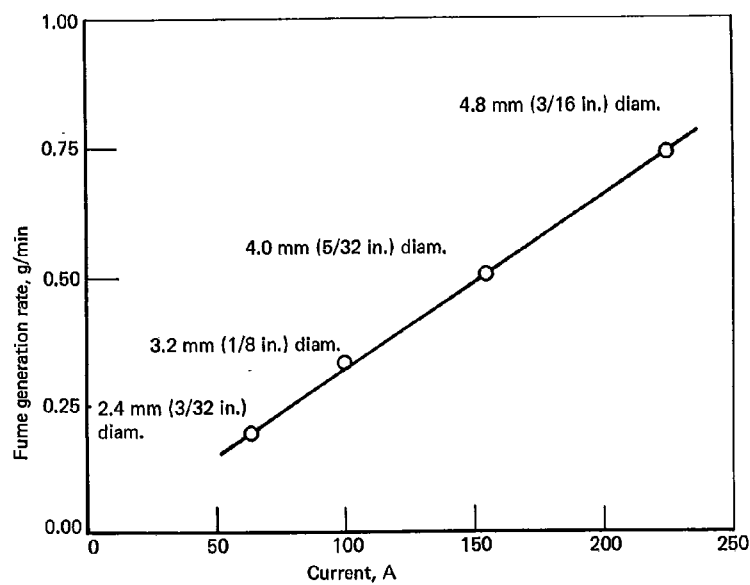


Fig. 2.12—Fume generation rates for E7018 covered electrodes with different diameters as a function of current

of fume generation rate on welding current. With approximately equal current densities in each electrode, the variation of fume generation rate with current was almost linear. Four E6010 and four E6013 electrodes were evaluated in a similar manner and similar results were obtained; these data are shown in Tables B33 and B34 respectively.

Arc Voltage—Arc Length Effects

Arc voltage and arc length are closely related welding parameters: for any given arc length, there is a corresponding value of voltage whose magnitude is determined by the characteristics of the electrode (resistivity, melting rate, etc.) and those of the welding process and power supply. During the investigation, the fume generation characteristics of selected electrodes as a function of voltage (measured across the electrodes) and arc length were studied. Because of the interrelationship between these variables, their effects on the rate at which fumes were produced were similar.

Previously discussed studies to evaluate the fume generation characteristics of a flux cored electrode, E70T-1 (41), were extended to include the effects of voltage. To investigate the dependency of fume genera-

tion rate on voltage, welding was done at high and low voltages near the low, middle, and high portions of the current range used for this electrode (330 to 600 amperes). For any given current, the "high" voltage was slightly below that at which the arc became unstable and difficult to control; the "low" voltage was just higher than that at which stubbing of the electrode occurred. The results obtained at the middle and high portions of the current range are shown in Fig. 2.13; tabular data are provided in Table B28. The results showed an increase in voltage was accompanied by an increase in the fume generation rate. Other investigators have reported similar results. In this instance, the effect of voltage was most pronounced at higher current levels.

The effects of arc voltage (or arc length) on the fume generation characteristics of an E6010 covered electrode were also examined. Welding was done at a nominal current of 150 amperes over a voltage range that extended from about 20 to 40 volts. Data on fume generation rates for this electrode are also plotted in Fig. 2.13; complete data on the results of this study are shown in Table B35. Although fumes were produced at different rates by the E6010 and E70T-1 electrodes, the trend toward increasing quantities of fumes at higher voltages was common to both.

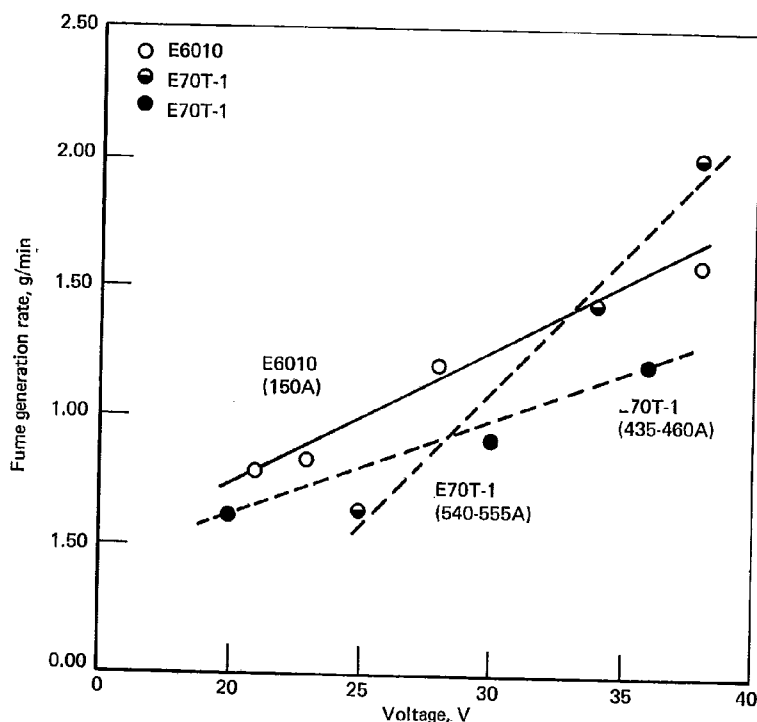


Fig. 2.13—Fume generation rates for an E6010 covered electrode and an E70T-1 flux cored electrode as a function of voltage at selected current levels

Arc length effects were studied with 4 mm (5/32 in.) diameter E6010, E6013, and E7018 electrodes. A video camera connected to a television unit and a video tape recorder were used to display and record arc length; current and voltage were monitored with a strip chart recorder.

Fume samples were obtained when welding was done with each electrode at selected arc lengths. To obtain the desired data, a welding arc was established and the power unit was adjusted to provide current at about 150 amperes. The arc was photographed with the video camera and the result was concurrently displayed on the television screen and stored on video tape for future use. Then, as the welder monitored the screen to maintain as constant an arc length as possible, a bead-on-plate weld was deposited and the fume sample was collected. The welding time was about 30 seconds. This process was repeated for each arc length.

The resulting data were analyzed to determine the effects of arc length on fume generation rates. To accomplish this objective, the data stored on the video tape

were displayed on the television screen and the average arc length over the welding interval was measured from the plate surface to the electrode tip. It should be emphasized that this was a subjective measurement, because the arc length varied during welding. Since current varied also, the fume generation rates were normalized at a current of 150 amperes to provide a common basis for comparison. The results of this investigation are summarized in Fig. 2.14; supporting data are provided in Table B36.

Fume generation rates increased with increasing arc length for all of the electrodes included in this investigation. The slope of the lines relating these variables indicated that arc length had slightly more effect on the rates at which fumes were produced by the E6010 and E6013 electrodes than on the rate at which fumes were produced by the E7018 electrode. The results of this investigation (i.e., the increase in fume generation rate with increasing arc length) are in general agreement with those observed by Kobayashi, Maki, and Ohe (Ref. 2.5).

In a related experiment, the welding current was

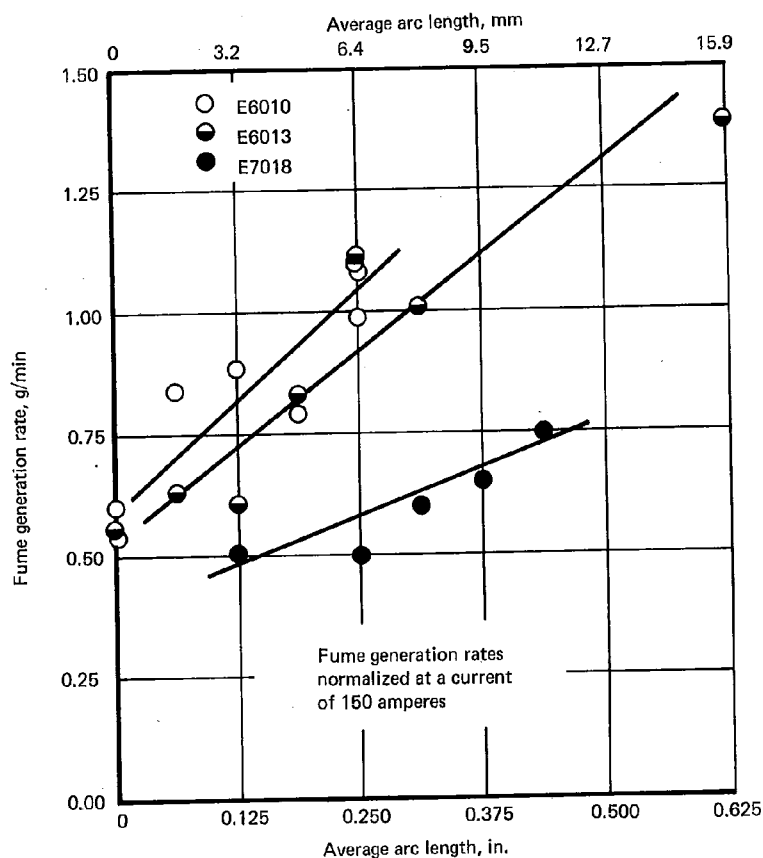


Fig. 2.14—Fume generation rates for selected covered electrodes as a function of arc length

initially established at 150 amperes for an arc length that would normally be used during welding. The current was not adjusted thereafter, but was allowed to vary with different arc lengths. For example, when the arc length was increased, voltage increased and current decreased. Fume samples were collected at selected arc lengths for E6010, E6013, and E7018 electrodes during welding intervals of about 30 seconds. Arc length data were recorded on video tape and analyzed later in the manner described previously. All fume generation rates were normalized to a common current of 150 amperes for comparison purposes. The results were similar to those discussed previously; that is, fume generation rates increased with increasing arc length (see Table B36).

Contact-Tube-To-Work Distance Effects

The distance between the end of the contact tube and the surface of the base plate is a variable that affects the melting and metal deposition rates in flux cored arc welding and gas metal arc welding. Since fume generation rates are closely associated with melting rates, the effects of contact tube-to-work distance were included in this investigation.

The fume generation characteristics of an E70T-1 flux cored electrode as a function of contact tube-to-work distance were determined. Welding was done at two current levels, nominally 450 and 520 amperes, and the

contact tube-to-work distance was varied from 19 mm (0.75 in.) to 38 mm (1.50 in.). As the contact tube-to-work distance was varied, the wire feed rate was adjusted to maintain the selected current level. The power supply voltage remained constant during these studies, even though it would be normally increased or decreased with changes in contact tube-to-work distance so that arc length could be controlled.

The following observations are based on an examination of the data presented in Tables B42 and B43 and in Fig. 2.15:

(1) At each current level, there was a gradual increase in metal deposition rate with increasing contact tube-to-work distance (Tables B42 and B43). When the contact tube-to-work distance increases, the wire feed speed must be increased to maintain a constant current level. The increased melting rate is accompanied by a higher deposition rate.

(2) For each current level, the fume generation rate remained essentially constant for each contact tube-to-work distance.

(3) The ratio of weight of fumes to weight of deposited metal decreased gradually with increasing contact tube-to-work distance.

(4) The effect of current on fume generation rate is evident in Fig. 2.15. At 450 amperes, the fume generation rate was about 1 g/min; at 520 amperes, the rate was about 1.3 g/min.

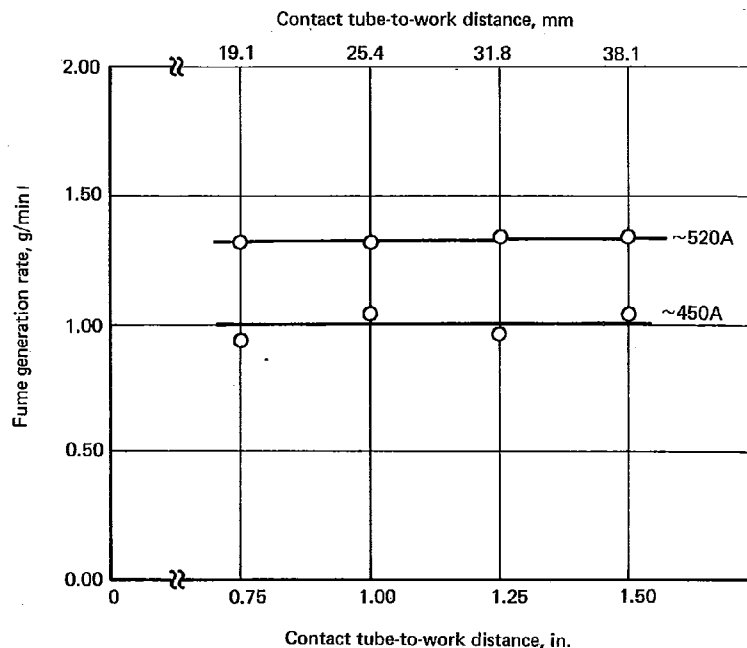


Fig. 2.15—Fume generation rate of a 2.4 mm (3/32 in.) E70T-1 flux cored electrode as a function of contact tube-to-work distance at selected constant current levels

Shielding Gas Effects

The shielding gas is a variable associated with the flux cored and gas metal arc welding processes, and it affects the rate at which fumes are produced during welding and the composition of the fumes. The type of shielding gas also affects the kind of gases to be found in the welding area.

The effects of shielding gases on fume generation rates have already been discussed in the review of the baseline data for flux cored and gas metal arc welding electrodes. These rates were highest when CO₂ or gas mixtures containing CO₂ were used to shield the welding arc.

Since the oxidation potential of the shielding gas affects the rate at which specific elements oxidize as they are vaporized from the tip of the electrode, studies were conducted to determine the effects of shielding gas type on the composition of the fumes produced by E70S-3 gas metal arc electrodes used for welding carbon steels. Each of the three E70S-3 electrodes included in this investigation was evaluated using welding conditions to produce the following transfer modes: (a) spray transfer with Ar-2 O₂ shielding, (b) spray transfer with Ar-9 CO₂ shielding, and (c) globular transfer with CO₂ shielding. The fume samples were collected on cellulose membrane filters and analyzed by atomic absorption procedures. The resulting

data plus the calculated weight percentages of each oxide are shown in Table 2.14 and the apparent trends are discussed below:

(1) Iron (iron oxide) contents were highest when welding was done in the spray transfer mode with either Ar-2 O₂ or Ar-9 CO₂ shielding and lowest when welding was done in the globular transfer mode with CO₂ shielding. These results are in agreement with those of Heile and Hill (Ref. 2.3).

(2) Manganese (manganese oxide) contents were highest when welding was done in either the spray transfer mode with Ar-9 CO₂ shielding or in the globular transfer mode with CO₂ shielding; this element (or elemental oxide) content was lowest when welding was done in the spray transfer mode with Ar-2 O₂ shielding. Here, the oxidation potential of the shielding gas had a slight effect on the contents of manganese (manganese oxide) in the fumes.

(3) Silicon (silicon dioxide) contents were highest when welding was done in the globular transfer mode with an oxidizing gas, CO₂. These results are also in agreement with those of Heile and Hill (Ref. 2.3). There was no apparent explanation for the low silicon content in the fumes produced by the E70S-3(54) and E70S-3(57) electrodes.

(4) Copper contents in the fumes appeared to be less

Table 2.14
Effects of shielding gas on fume composition

Electrode ¹	Shielding gas	Fume sample weight, g	Composition, weight %						
			Fe	(Fe ₂ O ₃)	Mn	(MnO ₂)	Si	(SiO ₂)	Cu
E70S-3 (54)	Ar-2 O ₂ ²	0.23	61.7	(88.2)	4.6	(7.3)	1.0	(1.6)	0.09
E70S-3 (54)	Ar-9 CO ₂	0.55	62.5	(89.4)	6.1	(9.6)	0.5	(0.8)	0.09
E70S-3 (54)	CO ₂	0.42	56.3	(80.5)	6.3	(10.0)	2.3	(3.6)	0.14
E70S-3 (57)	Ar-2 O ₂ ²	0.32	62.7	(89.7)	4.4	(7.0)	1.1	(1.7)	0.85
E70S-3 (57)	Ar-9 CO ₂	0.44	62.2	(88.9)	6.5	(10.3)	0.4	(0.6)	0.70
E70S-3 (57)	CO ₂	0.33	55.4	(79.2)	6.8	(10.7)	1.5	(2.4)	1.20
E70S-3 (58)	Ar-2 O ₂ ²	0.41	62.1	(88.8)	5.6	(8.8)	1.1	(1.7)	1.29
E70S-3 (58)	Ar-9 CO ₂	0.54	62.0	(88.7)	4.6	(7.3)	1.5	(2.4)	0.99
E70S-3 (58)	CO ₂	0.40	52.5	(75.1)	5.5	(8.7)	2.5	(3.9)	1.00

1. Welding Conditions:

For spray transfer welding with Ar-2 O₂ shielding
 Electrode No. 54: 35 V; 260-280 A
 Electrode No. 57: 35 V; 270-280 A
 Electrode No. 58: 34.5 V; 290-300 A

For globular transfer welding with CO₂ shielding
 Electrode No. 54: 36 V; 330-340 A
 Electrode No. 57: 35 V; 320 A
 Electrode No. 58: 32 V; 330 A

For spray transfer welding with Ar-9 CO₂ shielding
 Electrode No. 54: 34.5 V; 210-220 A
 Electrode No. 57: 35 V; 205-215 A
 Electrode No. 58: 35 V; 215-225 A

2. Average of three analyses.

a function of the shielding gas than were the other core wire elements and their oxides.

Effects of Iron Powder Additions

Investigation was made into the effects of iron powder additions on the fume generation characteristics of the two groups of mild steel electrodes listed below:

(1) High Titania Electrodes. This group included electrodes with high titania coverings and iron powder additions ranging from none (E6013) to moderate (E7014) to high (E7024).

(2) Low Hydrogen Electrodes. This group included electrodes with low hydrogen coverings and iron powder additions ranging from none (E7016) to moderate (E7018) to high (E7028).

These studies were conducted with 4 mm (5/32 in.) diameter electrodes, all of which were made by one producer. Welding was done at currents near the high end of the operating range. The results of this investigation are summarized in Table 2.15; detailed data are contained in Tables B37 and B38.

High Titania Electrodes. At the measured welding current, the fume generation rates for the E6013, E7014, and E7024 electrodes were very similar in magnitude (0.68 to 0.72 g/min) and appeared to be unaffected by the presence or absence of iron powder additions to the electrode coverings. This is not the case if the fume generation rates for these electrodes are compared at equivalent welding currents. When these rates were normalized to a current of 175 A, for example, the fume generation rates varied inversely with the amount of iron powder in the electrode covering.

The ratio of the weight of fumes to weight of deposited metal also varied inversely with the amount of iron powder in the covering when these electrodes were used at recommended current levels. Under these conditions, the E7024 electrode had the lowest ratio, because the fume generation rate for this electrode was low and the metal deposition rate was high.

Low Hydrogen Electrodes. At recommended current levels, the fume generation rates for the E7016 (no iron powder addition) and E7018 (moderate iron powder addition) electrodes were almost identical; the rate for the E7028 electrode (high iron powder addition) was twice as large. When the normalized rates for these electrodes were compared, they were very similar in magnitude (0.50 to 0.58 g/min). The rates at which fumes were produced appeared to be controlled by ingredients other than iron powder in the electrode covering. Calcium fluoride, a compound common to these low hydrogen electrodes, probably exerted a controlling influence on the rate at which fumes were produced.

Ratios of weight of fumes to weight of deposited metal for these electrodes were similar in magnitude.

Other Studies

Electrode Angle Effects. The effect of electrode angle on

the rate at which fumes are produced by covered electrodes was studied with 4 mm (5/32 in.) diameter E6010, E6013, and E7018 electrodes. Each electrode was evaluated at angles of 30, 60, and 90 degrees to the workpiece; a tubular guide for the electrode was used to establish and maintain the desired electrode angle. Bead-on-plate welds were deposited with each electrode at a nominal current of 150 A. The results are shown in Fig. 2.16; supporting data are presented in Table B39.

For all electrodes examined, the data indicated a gradual decrease in the fume generation rate as the angle between the electrode and workpiece increased toward 90 degrees. This result agrees with the findings of other investigators (Refs. 2.5 and 2.18). However, care should be observed in interpreting the data presented strictly in terms of an electrode angle effect, because a lengthening of the arc probably occurred as the electrode angle decreased. As indicated in the section on arc length, fume generation rates are affected substantially by changes in this variable.

Two sets of operating conditions that produced arc lengths differing by about 1.6 mm (1/16 in.) were used with the E6010 electrode; data obtained under those conditions are also included in Fig. 2.16. The curves representing fume generation rates at various angles were separated by an amount largely attributable to the effect of

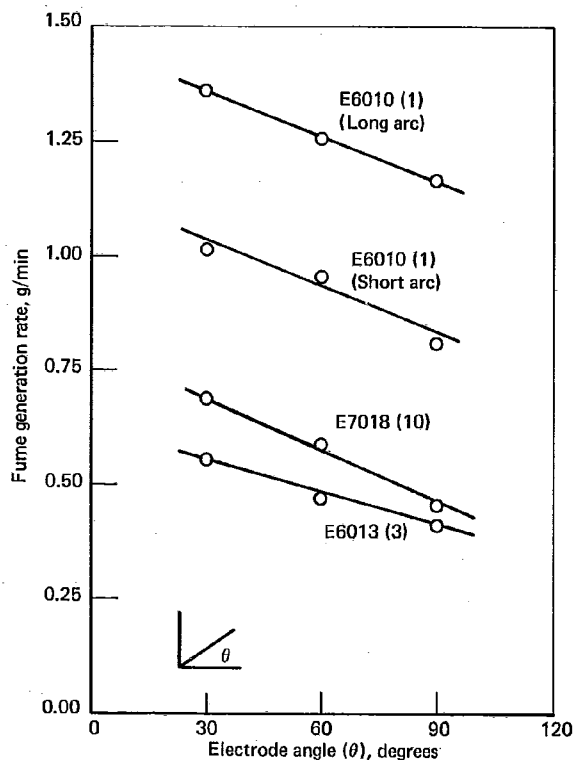


Fig. 2.16—Effect of electrode angle on the fume generation rates of covered electrodes

Table 2.15
Summary of data on effects of iron powder on fume generation
characteristics of high titania and low hydrogen covered electrodes

Electrode	Covering	Current, A (nominal)	Fume generation rate		Weight of fume/ wgt. of deposited metal, g/kg ²
			Measured, g/min	Normalized ¹ , g/min	
E6013	High titania	165	0.73	0.81	29.86
E7014	High titania	175	0.72	0.75	23.72
E7024	High titania	210	0.68	0.47	12.13
E7016	Low hydrogen	170	0.50	0.51	20.84
E7018	Low hydrogen	175	0.51	0.50	18.39
E7024	Low hydrogen	230	1.03	0.58	21.27

1. Fume generation rates normalized to 175 A.

2. g/kg ÷ 10 = weight of fume expressed as a percentage of deposit weight.

arc length differences; however, in both instances, the rates decreased with increasing electrode angle by about the same amount.

Welding with covered electrodes is done mostly at large (>60 degree) angles between the electrode and workpiece, so problems with fumes are minimized. It is important to be aware that increased amounts of fumes can be expected when welding is done under confined conditions where the electrode angle might be restricted to small values.

Base Plate Effects. Fume generation characteristics for the covered, flux cored, and solid electrodes investigated during this program were determined with base plates whose composition was similar to that of the core wire or sheath. That is, E6010 and E70T-1 electrodes were evaluated with carbon steel plate, E410-15 electrodes with 400-series stainless steel plate, and so on. Since the base plate has relatively little effect on the production of fumes, the need to match the base plate to the electrode was questioned, particularly with respect to the evaluation of stainless steel electrodes. To resolve this question, fume samples for gravimetric and chemical analyses were collected during the deposition of stainless steel bead-on-plate welds on carbon steel and stainless steel plates. Welding was done with a 4 mm (5/32 in.) diameter E316-16 covered electrode at baseline conditions. The experimental results are discussed below with the aid of Tables 2.16 and 2.17.

(1) As indicated in Table 2.16, fume generation rates and ratios of weight of fumes to weight of deposited metal were unaffected by the type of base metal used during welding. Thus, either carbon steel or stainless steel could be used with equal facility to evaluate stainless steel electrodes in terms of their fume generation rates. Caution in extrapolating these results to other electrodes is advised.

(2) The composition of the fumes did reflect the

composition of the base metal upon which the welds were deposited as well as that of the electrode. When the E316-16 electrode was evaluated on stainless steel, the fumes contained higher contents of manganese, nickel, and chromium than when this electrode was used on carbon steel (Table 2.17). The effects of the electrode itself on fume composition can be estimated by examining the composition of the fumes produced when welds were deposited on carbon steel. The difference between the contents of manganese, nickel, and chromium in this sample and in the sample collected when welding was done on stainless steel represents the effects of the stainless steel base plate on fume composition. It was concluded that electrode and base plate should be matched if fume compositions are to be determined.

Diameter Effects with Flux Cored Electrodes. The fume generation characteristics of a 1.6 mm (1/16 in.) diameter E70T-1 electrode were compared to those of a 2.4 mm (3/32 in.) diameter electrode made by the same manufacturer. Welding was done at current levels appropriate for the respective electrodes and CO₂ was used for shielding (Table B41). Data on the "as measured" and "normalized" fume generation rates are presented below:

Electrode	Electrode diam., in. (mm)	Welding current, A	Fume generation rate, g/min.	
			Measured	Normalized*
E70T-1 (40)	3/32 (2.4)	480	1.36	1.36
E70T-1 (45)	1/16 (1.6)	330	1.01	2.14

*Fume generation rates normalized to a current of 480 A.

The measured fume generation rate for the small diameter electrode was less than that associated with the large diameter electrode. However, when the effect of current on this characteristic was taken into account by normalizing the fume generation rates to a common current (480 A

Table 2.16
Effect of base plate on average fume generation characteristics
of 4 mm (5/32 in.) diameter E316-16 covered electrode

Characteristic	Base plate	
	Carbon steel	Stainless steel
Fume generation rate, g/min.	0.24	0.24
Weight of fume/weight of deposited metal, g/kg*	9.96	9.87

*g/kg ÷ 10 = %

Table 2.17
Composition of carbon steel and stainless steel base plate
and composition of fume samples

Type	Composition, weight %				
	Fe	Mn	Si	Cr	Ni
	Base plate				
Carbon steel	Bal.	0.68	<0.01	---	---
Stainless steel (Type 304)	Bal.	1.70	0.41	19.43	8.31
	Fumes				
Electrode/base plate					
E316-16/carbon steel	7.85	7.53	<0.01	4.85	1.03
E316-16/stainless steel	8.16	7.80	<0.01	5.60	1.21

in this case), more fumes were produced by the small diameter electrode than by the large diameter one. Fume generation rates are dependent upon the rate at which the electrode is consumed. If two electrodes with different diameters are used at the same current level, the melting rate for the smaller of the two electrodes will be greater in the small diameter electrode. The effect of increased I^2R heating in the smaller electrode probably also contributed to increased melting rate. The effect of I^2R heating on deposition rates was studied by Wilson, Claussen, and Jackson (Ref. 2.22).

Section IID. Analytical Studies

Various analytical methods were used to determine the presence of selected constituents in the fumes produced during arc welding operations. Some of the characteristics of these methods are discussed as follows:

(1) Optical emission spectroscopy yields a wealth of analytical data because 70 or more elements can be detected simultaneously and their content can be esti-

mated on a semiquantitative basis. It is best suited for accurately determining the presence of elements that are present in small amounts. This method is most valuable when the elements in question are present in concentrations of 1 percent or less. If elements are present in large amounts, concentrations are often expressed in percentage ranges, and other techniques (e.g., atomic absorption) must be used to obtain greater accuracy. In the case of welding fumes, optical emission spectroscopy can provide an overview of most of the elements present in the fume sample, regardless of their origin; i.e., from the core wire or sheath, electrode covering or flux, or base plate. This method was used during this program in studies to characterize the nature of welding fumes, and the results have been presented in a previous section of this report. It was not used more extensively because capital equipment costs for optical emission spectroscopy are high, and such equipment is not as readily available in industry as that used with other analytical methods.

(2) Atomic absorption analysis is also capable of determining the presence of about 70 elements, but the concentration of each element must be detected individually. Analytical costs per individual element are not high, but they can be appreciable if the sample contains

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several elements (e.g., the fumes produced by stainless steel or nickel-base electrodes). This method is better suited than optical emission spectroscopy for the detection of elements that are present in large amounts, and the detection accuracy is excellent. Equipment for atomic absorption analysis is reasonable in cost and readily available in industry. Optical emission spectroscopy combined with atomic absorption analyses of elements present in large concentrations provide reliable data on fume sample compositions.

(3) Classical chemical analysis procedures have been developed to detect the presence of most elements and compounds. Insofar as welding fumes are concerned, these methods are most useful in determining constituents whose presence cannot be detected by optical emission spectroscopy or atomic absorption analysis (e.g., fluorides, chlorides, gases, etc.).

Analysis of Fume

In this program, atomic absorption analysis was selected as the primary analytical technique for detecting elemental fume constituents because equipment for conducting such analyses is commonly available and relatively simple to use. However, by agreement with the AWS Research Committee, this method was used only to detect the major constituents that originated in the core wire or electrode sheath (i.e., iron, manganese, and silicon in the case of fumes produced by low carbon steel covered or flux cored electrodes) because of (a) the large number of samples to be analyzed and (b) the need to detect constituents on an element-by-element basis. As a result, analytical data on the composition of fumes associated with covered or flux cored electrodes do not total 100 percent because they do not include all of the contents of constituents originating in the electrode covering or flux (e.g., sodium, calcium, titanium, etc.). In some instances, these constituents represent a major fraction of the constituents in the fumes. In the case of fumes produced by solid gas metal arc electrodes, the analytical data more nearly approach 100 percent as a total, assuming that most elements are present in the oxide form.

To supplement these data, fluoride contents in the fumes produced by many of the low hydrogen electrodes were determined by wet chemical analysis. Different analytical techniques are needed to determine total fluorides and water-soluble fluorides. Total fluoride contents in the fumes produced by most of the low hydrogen covered electrodes investigated during this program were obtained. Water-soluble fluorides (but not total fluorides) were determined for several other electrodes. In the course of these studies, both total and water-soluble fluorides were determined in samples of the fumes produced by representative E7018 covered and E70T-1 flux cored electrodes provided by the AWS Subcommittee on Sampling. The results are shown below.

Electrode	Fluoride content of fumes, wgt. %		
	Total	Water-soluble	Water-insoluble*
E7018	22.1	5.9	16.2
E70T-1	0.23	0.16	0.07

*Obtained by subtraction.

The data indicate that a large fraction of the fluorides in the fumes produced by the E7018 electrode was insoluble in water; this result may be attributable to the presence of calcium fluoride in the fumes. This compound, a common and major ingredient in low hydrogen electrode coverings and fluxes, is soluble in water to a limited degree only. The fluoride content of the fumes associated with the E70T-1 flux cored electrode was negligible from the hygienic viewpoint; the fumes generated by the E7018 electrode contained appreciable fluorides.

Concentrations of selected elements in the fumes produced by representative covered, flux cored, and solid electrodes investigated during this program were determined by atomic absorption analysis of fume samples collected on cellulose membrane filters. The analytical results are shown in Table 2.18 along with supplementary data on fluorides in the fumes produced by some of these electrodes. With few exceptions (e.g., carbon steel electrodes used for gas metal arc welding), the data represent the results obtained from the analysis of one sample per electrode.

The following comments are based on a review of the data contained in Table 2.18:

(1) When converted to their common oxide form, the constituents of fumes produced by solid gas metal arc welding electrodes generally totalled in the 90 percent range. Lower totals were observed for constituents associated with the fumes generated by ER5356, ERNiCu-7, Inconel 625, and ERCu electrodes.

(2) The constituents (in oxide form) of fumes produced by covered and flux cored electrodes did not approach 100 percent as a total because concentrations of elements associated with the electrode covering or flux were not determined by analysis and, as a result, could not be included in such compilations. Fume constituent totals were highest for electrodes with relatively thin coverings (E6010 and E6013) and lowest for electrodes with thick coverings (E7018 and E7024). This is an indirect indication of the contribution of the electrode covering to the overall fume generation rate.

(3) The fluoride content of the fumes produced by the E8018 C3, E9018 B3, and E316-15 covered electrodes was high in comparison to that observed with other electrodes. This may be characteristic of these electrodes since they were all produced by the same manufacturer.

(4) The fluoride content (water-soluble) of the fumes associated with four of the E70T-1 electrodes included in this investigation was small (0.06 to 0.31 percent). Much higher fluoride contents (6.33 and 8.68 percent) were observed in the fume produced by two

Table 2.18
Concentrations of selected constituents in the fumes produced by arc welding electrodes
(Analyses by atomic absorption technique)

Electrode	Code	Fume sample weight, g	Concentration, weight percent										Other	
			Fe	Mn	Si	Ni	Cu	Cr	Mo	Al	Mg	F		
Covered electrodes														
E6010 (IP)	1	0.49	47.5	3.0	5.7	---	---	---	---	---	---	---	---	---
E6010 (IP)	2	0.35	49.6	3.4	6.5	---	---	---	---	---	---	---	---	---
E6010 (IP)	11	0.56	41.6	3.4	3.7	---	---	---	---	---	---	---	---	---
E6013	4	0.16	61.4	5.1	12.2	---	---	---	---	---	---	---	---	---
E6013	6	0.08	45.0	5.5	15.0	---	---	---	---	---	---	---	---	---
E6013	3	0.27	62.2	4.1	11.2	---	---	---	---	---	---	---	---	---
E7018	5	0.26	26.1	4.5	<0.2	---	---	---	---	---	---	13.1 ¹	---	---
E7018	12	0.30	28.7	4.1	<0.2	---	---	---	---	---	---	14.0 ¹	---	---
E7018	10	0.26	24.2	3.6	<0.2	---	---	---	---	---	---	15.0 ¹	---	---
E7024	7	0.30	30.2	5.3	18.3	---	---	---	---	---	---	---	---	---
E7024	8	0.31	29.5	5.6	19.7	---	---	---	---	---	---	---	---	---
E7024	9	0.31	33.3	7.8	13.2	---	---	---	---	---	---	---	---	---
E6013 ³	34	0.25	41.4	---	---	---	---	---	---	---	---	---	---	---
E7014 ³	30	0.23	39.0	---	---	---	---	---	---	---	---	---	---	---
E7024 ³	35	0.27	27.8	---	---	---	---	---	---	---	---	---	---	---
E7016 ³	29	0.21	32.7	---	---	---	---	---	---	---	---	15.2 ¹	---	---
E7018 ³	36	0.22	27.8	---	---	---	---	---	---	---	---	12.7 ¹	---	---
E7028 ³	32	0.42	38.1	---	---	---	---	---	---	---	---	11.6 ¹	---	---
E8018 C3	14	0.12	45.2	7.2	---	0.3	---	0.1	<0.1	---	---	35.8 ¹	---	---
E9018 B3	17	0.16	21.9	5.9	---	0.1	---	1.6	<0.1	---	---	28.1 ¹	---	---
E316-15	22	0.15	8.4	7.7	---	1.1	---	5.8	<0.1	---	---	---	---	---
E316-16	20	0.17	10.0	8.8	---	1.5	---	6.5	<0.1	---	---	17.2 ¹	---	---
E410-16	21	0.11	33.1	5.2	---	<0.1	---	---	---	---	---	10.0 ¹	---	---
ENi-Cl	28	0.35	2.5	0.3	---	6.9	---	<0.1	---	---	---	---	---	---
ENiCu-2	33	0.31	0.1	2.1	---	4.2	---	6.2	---	---	---	---	---	---
Inconel 625 ⁷	62	0.25	0.6	---	---	4.6	---	0.7	2.1	---	---	---	0.1Co-0.1W-2.4Ca-4.9Ti	---
Haynes C-276 ⁸	69	0.35	0.3	0.3	---	1.1	---	2.5	0.6	1.0	1.4	5.9 ¹	7.7Co-1.3W-2.4Ca-5.3Ti	---
Haynes 25 ⁸	70	0.25	---	4.6	---	1.8	---	6.9	---	1.1	0.1	7.7 ¹	---	---
Flux cored electrodes														
E70T-1	40	0.53	34.4	7.1	3.7	---	---	---	---	---	---	0.06 ²	---	---
E70T-1	41	0.60	25.2	13.5	7.5	---	---	---	---	---	---	0.06 ²	---	---
E70T-1	42	0.91	33.6	9.7	2.2	---	---	---	---	---	---	8.68 ²	---	---
E70T-1	45	0.51	46.1	12.4	5.2	---	---	---	---	---	---	0.17 ²	---	---
E70T-1	46	0.63	41.2	6.2	5.4	---	---	---	---	---	---	0.31 ²	---	---
E70T-1	47	0.89	37.9	6.4	1.0	---	---	---	---	---	---	6.33 ²	---	---

Table 2.18 (cont.)
Concentrations of selected constituents in the fumes produced by arc welding electrodes
(Analyses by atomic absorption technique)

Electrode	Code	Fume sample weight, g	Concentration, weight percent											
			Fe	Mn	Si	Ni	Cu	Cr	Mo	Al	Mg	F	Other	
Flux cored electrodes (cont.)														
E70T-4	48	1.45	11.5	3.3	<0.05	<0.01	---	---	---	---	---	2.73 ²	---	---
E70T-4	49	0.98	16.2	4.6	<0.05	<0.01	---	---	---	---	---	0.84 ²	---	---
E70T-4	56	0.95	15.1	1.0	<0.05	<0.01	---	---	---	---	---	1.84 ²	---	---
E70T-5	44	0.90	26.7	11.3	<0.05	---	---	---	---	---	---	2.63 ²	---	---
E70T-5	50	0.61	29.2	10.9	0.09	---	---	---	---	---	---	4.80 ²	---	---
316L	55	0.65	12.4	7.3	0.05	1.06	---	12.5	0.34	---	---	11.5 ²	---	---
Gas metal arc electrodes														
E70S-3 ⁴	54	---	63.7	5.3	0.05	---	0.11	---	---	---	---	---	---	---
E70S-3 ⁴	54	0.54	61.0	3.6	1.1	---	0.07	---	---	---	---	---	---	---
E70S-3 ⁴	54	0.55	60.4	5.0	1.9	---	0.09	---	---	---	---	---	---	---
E70S-3 ⁵	54	0.55	62.5	6.1	0.5	---	0.09	---	---	---	---	---	---	---
E70S-3 ⁶	54	0.42	56.3	6.3	2.3	---	0.14	---	---	---	---	---	---	---
E70S-3 ⁴	57	0.23	65.7	3.8	0.8	---	0.60	---	---	---	---	---	---	---
E70S-3 ⁴	57	0.29	61.2	3.5	0.6	---	1.20	---	---	---	---	---	---	---
E70S-3 ⁴	57	0.44	61.1	5.8	1.8	---	0.74	---	---	---	---	---	---	---
E70S-3 ⁵	57	0.44	62.2	6.5	0.4	---	0.70	---	---	---	---	---	---	---
E70S-3 ⁶	57	0.33	52.2	6.8	1.5	---	1.00	---	---	---	---	---	---	---
E70S-3 ⁴	58	0.23	62.5	8.5	0.5	---	1.00	---	---	---	---	---	---	---
E70S-3 ⁴	58	0.49	60.1	3.4	1.0	---	1.80	---	---	---	---	---	---	---
E70S-3 ⁴	58	0.50	63.6	4.8	1.7	---	1.08	---	---	---	---	---	---	---
E70S-3 ⁵	58	0.54	62.0	4.6	1.5	---	0.99	---	---	---	---	---	---	---
E70S-3 ⁶	58	0.40	55.4	5.5	2.5	---	1.20	---	---	---	---	---	---	---
E70S-5	59	0.11	61.7	5.8	0.93	---	1.75	---	---	---	---	---	---	---
ER5356	60	1.06	---	---	---	---	---	---	---	38.0	3.8	---	---	---
ER4043	61	0.10	---	---	1.7	---	---	---	---	46.2	---	---	---	---
ERNiCu-7	64	0.13	5.0	1.1	0.65	22.1	44.4	<0.01	---	---	---	---	---	---
Inconel 625 ⁷	53	0.07	1.9	---	---	27.2	0.69	15.4	2.1	---	---	---	---	---
Haynes C-276 ⁸	68	0.25	3.6	1.0	---	32.5	---	8.2	16.2	0.4	---	---	---	3.2W
Haynes 25 ⁸	71	0.07	---	15.4	---	7.1	---	14.9	---	0.3	---	---	---	1.0W-33.5 Co
ERCuAl-A2	75	0.38	---	---	---	---	70.5	---	---	3.4	---	---	---	---
ERCu	76	0.31	---	---	---	---	66.0	---	---	---	---	---	---	---

Notes.

1. Total fluorides
2. Water-soluble fluorides
3. These electrodes were used to study the effect of iron powder additions on fume generation rates. Thus, only iron was determined in the analysis.
4. Shielding gas: A-2 O₂
5. Shielding gas: A-9 CO₂
6. Shielding gas: CO₂
7. TM, International Nickel Company
8. TM, Stellite Division, Cabot Corporation

E70T-1 electrodes, each of which was made by a different producer. As discussed by Smith (Ref. 2.17), the fluxes of some E70T-1 electrodes contain appreciable amounts of calcium fluoride to form a basic type slag.

Fume Characterization

A study was undertaken to characterize the fumes associated with various welding operations in terms of composition, the presence or absence of crystalline phases, and particle morphology. The fumes produced by electrodes used for shielded metal arc welding (E7024 and E410-16) and flux cored arc welding (E70T-1, E70T-4, and E70T-5) were analyzed for elemental composition by optical emission spectroscopy (OES) and for crystalline phases by x-ray diffraction (XRD). Scanning electron microscopy (SEM) was used to study particle morphology. Semiquantitative results of the OES analysis of the fume samples are shown in Table 2.19.

Optical emission spectroscopy is capable of detecting the presence of 70 or more elements on a semiquantita-

tive basis. Thus, totals of data for the individual fume samples listed in Table 2.19 may approach 100 percent, if the elemental fume constituents are converted to their common oxide forms. In some instances, elemental concentrations are expressed in percentage ranges, if the element is present in large amounts. Another analytical method (atomic absorption, wet chemistry, etc.) must be used to achieve more accuracy. Only one crystalline phase, iron oxide (Fe_3O_4 , or magnetite), was detected by XRD in the fumes produced by the covered electrodes; manganese was probably present in this phase also since it can replace iron in the crystal lattice. Crystalline phases containing silicon were not detected. However, since silicon was detected in the fumes produced by the E7024 and E410-16 electrodes, it was probably present as a glassy SiO_2 phase along with potassium and sodium. The x-ray diffraction pattern from the fumes produced by the E410-16 electrode had an extra diffraction line whose presence was attributed to a chromium compound.

In the fumes produced by the flux cored electrodes,

Table 2.19
Elemental composition of fumes produced by various electrodes¹
as determined by optical emission spectroscopy

Element	Composition, weight percent					
	E7024 (7)	E7024 (8)	E410-16 (21)	E70T-1 (42)	E70T-4 (49)	E70T-5 (50)
Fe	20.0-30.0	20.0-30.0	10.0-20.0	30.0-40.0	15.0-25.0	30.0-40.0
Si	10.0-20.0	5.0-10.0	2.0-3.0	2.0-3.0	0.1	2.0-3.0
K	8.0-12.0	8.0-12.0	10.0-20.0	1.0	2.0	4.0-6.0
Na	3.0-6.0	3.0-6.0	4.0-8.0	4.0-6.0	<0.1	1.0
Mn	2.0-4.0	2.0-4.0	1.0-2.0	4.0-6.0	2.0-3.0	4.0-6.0
Ca	0.1	0.5	2.0-4.0	0.1	15.0-25.0	8.0-12.0
Zn	≤0.1	<0.1	0.1	<0.1	<0.1	<0.1
Ti	0.5	0.3	0.4	0.5	<0.01	0.2
Pb	0.2	0.2	0.01	<0.01	0.2	0.02
Al	0.1	0.05	0.5	0.4	7.0-10.0	1.0-2.0
Sn	0.1	0.1	0.2	0.01	<0.01	<0.01
Cr	0.01	0.01	5.0-10.0	0.01	<0.01	<0.01
B	0.01	0.5	0.2	<0.01	<0.01	<0.01
Mg	0.01	0.03	0.3	0.02	7.0-10.0	0.2
Mo	0.005	0.005	0.05	<0.01	<0.01	<0.01
V	0.01	<0.01	0.03	<0.01	<0.01	0.02
Cu	0.05	0.1	0.1	0.1	0.01	0.02
Ni	0.005	0.01	0.05	0.01	<0.01	<0.01
Co	---	<0.01	0.01	<0.01	<0.01	<0.01
Ba	---	<0.01	0.03	0.01	0.05	0.03
Zr	---	---	---	0.1	<0.01	0.03
Sr	---	---	---	<0.01	<0.01	<0.01

1. The number in parentheses following the electrode designation is the code number identifying the specific electrode.

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the major crystalline phase detected was Fe_3O_4 ; manganese was probably present in this phase as well. In addition, a crystalline calcium fluoride phase (CaF_2 , or fluorite) was detected in the fumes associated with the E70T-4 and E70T-5 electrodes. Although magnesium was present as a major constituent in the fumes produced by the E70T-4 electrode, crystalline phases containing magnesium were not detected.

The initial SEM examination of samples of the fumes produced by E7024 and E410-16 covered electrodes revealed the presence of rounded particles 4 to 40 μm in diameter; structures that were obviously crystalline were not evident in the SEM micrographs (Figs. 2.17a and 2.17b). Very fine fume particles were not visible in the micrographs, probably because of the manner in which the samples were prepared for examination. To overcome this deficiency, silver membrane filters capable of capturing and retaining particles less than one micrometer in diameter were used to obtain additional samples of E7024 fumes for study by SEM. SEM micrographs of some very fine fume particles are shown in Fig. 2.18a and 2.18b. Semiquantitative analyses of individual fume particles in an area containing extremely fine particles are presented in Table 2.20. Morphologically, silicon was not present in the form of crystalline silica.

In SEM analysis, the relative intensity of the x-ray energy from individual elements is detected in counts/second, and the results are displayed on a cathode ray tube screen. This analytical method is semiquantitative unless standards are available and the effects of absorption and intensity are taken into account. In the SEM analyses, the contents of individual elements totalled 100 percent because the relative intensities were normalized.

SEM studies of the fumes associated with flux cored electrodes were also conducted. Many relatively small, irregularly-shaped particles were observed, but crystalline structures were not detected.

Gas Detection

Studies to detect the presence (or absence) of selected gases (carbon monoxide and nitrogen dioxide) produced during arc welding operations were conducted using gas

detector tubes containing ready-to-use stable chemicals which provide a colorimetric indication when specific gases are present. In practice, a measured volume of air is drawn through the tube and the resulting strain length is measured and related to the gas concentration by means of a calibration chart.

Two gases, carbon monoxide and nitrogen dioxide, were of specific interest because they are frequently present during arc welding operations. While ozone was also of interest, its detection with gas detector tubes is subject to interference by other airborne contaminants, and attempts to detect ozone in this manner were not made. Ozone is best detected by instruments equipped to monitor the chemiluminescent reaction between ethylene and ozone. The AWS publication, "The Welding Environment," lists several references concerned with ozone in the vicinity of arc welding processes (Refs. 2.10 and 2.12).

For this work, the appropriate gas detector tube was mounted in the apex of the fume collection chamber. Welding was done with representative covered, flux cored, and solid gas metal arc electrodes at conditions similar to those used in obtaining baseline fume generation data for these electrodes. During the welding and sampling interval, the gases were permitted to rise in the chamber by convection and escape through the open filter holder.

The following comments are based on a study of the data in Table 2.21:

(1) Unless ventilation is provided, carbon monoxide (CO) may present a problem during welding with processes in which the arc is shielded by CO_2 or gas mixtures containing CO_2 ; e.g., flux cored arc welding and gas metal arc welding. Carbon monoxide in inconsequential amounts may also be present during shielded metal arc welding.

(2) Nitrogen dioxide presents a potential problem based on published ACGIH threshold limit values when welding is done with processes in which the arc is shielded by argon or gas mixtures containing large amounts of argon.

The trends observed in this study were in agreement with the results obtained by other investigators. The

Table 2.20
Composition of fine fume particles from an E7024 electrode
by scanning electron microprobe analysis

Particle	Composition, percent of counts						
	Fe	Mn	Si	Ti	Al	K	Ca
A	25	7	19	35	---	8	6
B	7	5	13	47	3	16	9
C	98	---	2	---	---	---	---
Scan area	34	8	39	---	---	20	---

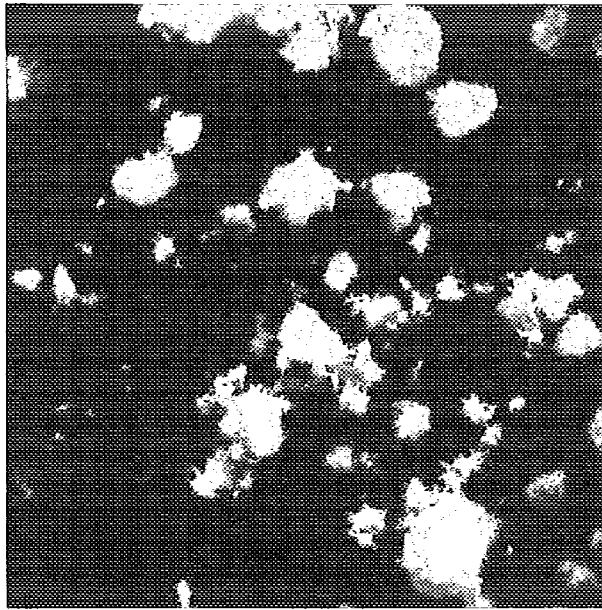


Fig. 2.17A—Scanning electron micrograph of fume from E7024 (8) electrode (magnification x 500)

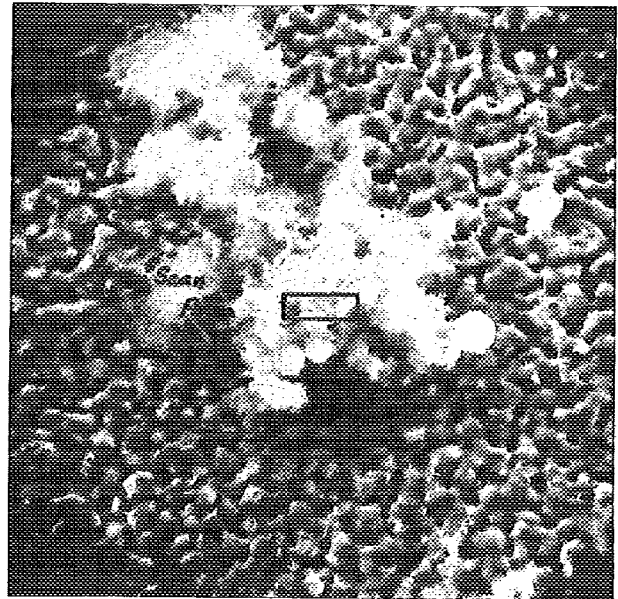


Fig. 2.18A—Fine fume from E7024 Electrode (Background is Flotronic silver membrane)

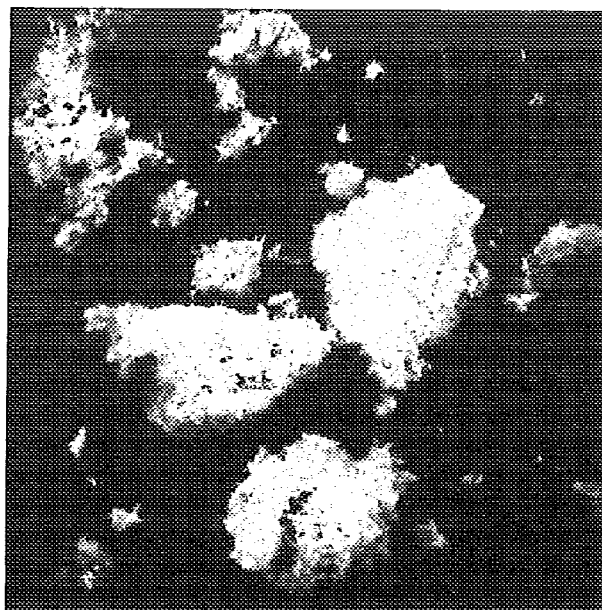


Fig. 2.17B—Scanning electron micrograph of fume from E410-16 (21) electrode (magnification x 500)

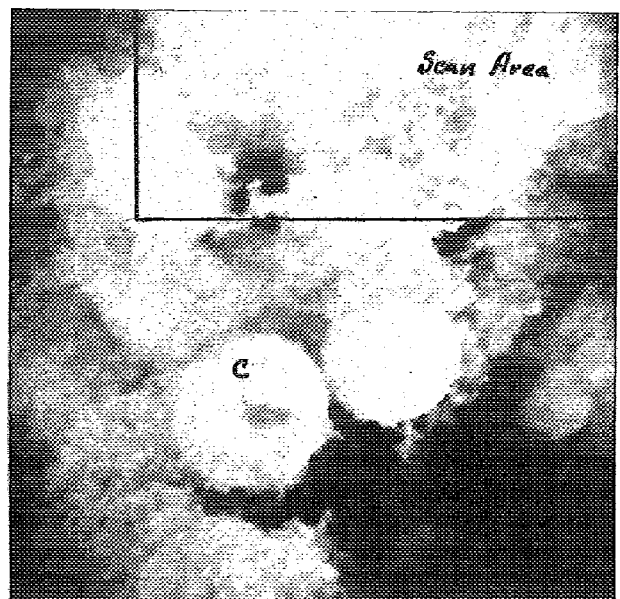


Fig. 2.18B—Fine fume from E7024 electrode

Table 2.21
Analyses of gases associated with arc welding

Electrode (code) ²	Gases (ppm) ¹		Supplementary shielding
	CO	NO ₂	
E6010 (11)	5	---	None
E6010 (1)	5	---	None
E6013 (3)	5	---	None
E6013 (4)	3	---	None
E7018 (10)	7.5	---	None
E7018 (12)	7	---	None
E7024 (7)	3	---	None
E7024 (9)	10	---	None
E8018 C3 (13)	10	---	None
E8018 C3 (15)	5	---	None
E9018 B3 (18)	5	---	None
E9018 B3 (16)	5	---	None
E316-15 (27)	8	0.25	None
E316-16 (27)	5	0.25	None
ENiCu 2 (33)	3	0.25	None
E70T-1 (40)	100	0.50	CO ₂
E70T-1 (40)	50	0.75	Ar-25 CO ₂
E70T-1 (41)	80	0.50	CO ₂
E70T-1 (41)	50	0.75	Ar-25 CO ₂
E70T-4 (50)	---	0.50	None
E70T-5 (44)	50	0.50	CO ₂
E70S-3 (58)	80	0.75	Ar-9 CO ₂
E70S-3 (58)	20	1.50	Ar-2 O ₂
E70S-3 (58)	150	0.25	CO ₂
E5356 (60)	---	1.00	Ar
Inconel 625	---	7.00	Ar

1. A dash (---) signifies that CO or NO₂ was not present in detectable amounts.

2. The number in parentheses following the electrode designation is the code number identifying the specific electrode.

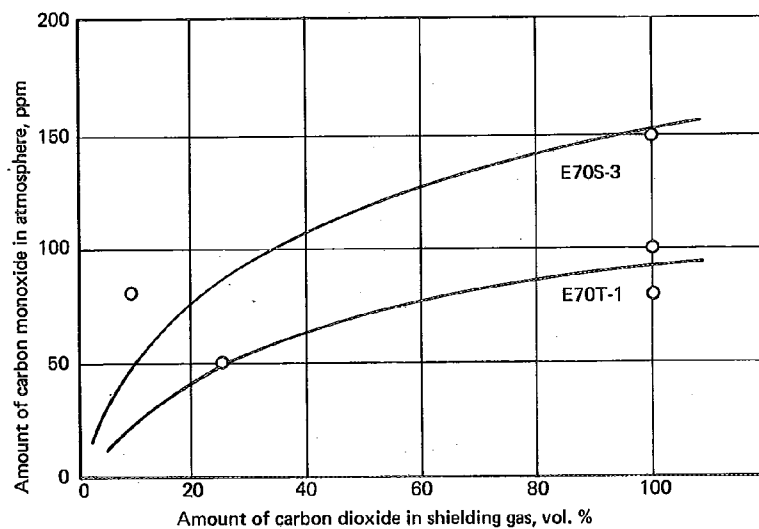


Fig. 2.19--Content of carbon monoxide in the atmosphere as a function of the amount of carbon dioxide in the shielding gas during gas metal arc and flux cored arc welding

concentrations of carbon monoxide and nitrogen dioxide in the vicinity of production welding operations may differ substantially from those obtained in the fume collection chamber because of the dilution of these gases by natural or artificial ventilation.

In gas shielded welding operations, problems with carbon monoxide can be minimized by the use of argon or argon-based shielding gases (Ar-2 O₂, Ar-9 CO₂, etc.).

The data in Table 2.18 can be used to establish a relationship between the amount of carbon dioxide in the shielding gas and the amount of carbon monoxide in the welding atmosphere (Fig. 2.19). As indicated, carbon monoxide concentrations rose gradually as the amount of carbon dioxide in the shielding gas increased from 0 to 100 percent. Additional data points would be needed to define this relationship with more accuracy.

Section IIE. Effect of Humidity on Fume Sampling Results

Early during Task 1 on arc welding fumes and gases of the American Welding Society research program "Improving the Welding Environment," the effect of humidity changes in the sampling area on the consistency of fume sampling results was examined. These studies were done at the request of the AWS Subcommittee on Sampling. The objective was to verify the procedures established by the working document "AWS Standard Method for Shop Sampling the Welding Environment" (July 30, 1975). As outlined, the study involved the collection of fume samples under low, medium, and high humidity conditions. The welding electrodes used were:

- (1) E70S-3, 0.045 in. (1.1 mm) diameter (low fuming type)
- (2) E70T-4, 0.120 in. (3 mm) diameter (high fuming type)

Welding was done at currents near the high end of the operating range (i.e., at about three-fourths of maximum recommended current for each electrode). For each humidity condition, replicate fume samples (3) were collected using a helmet sampler and a lapel sampler. The results of the effect of humidity on fume sampling results are reviewed hereinafter.

Sampling Area

Fume sampling was done in an environmentally controlled laboratory meeting Federal Clean Room Specifications. Since there was a laminar flow of air through this laboratory, an area near the air inlet was curtained off to produce a space for locating the welding equipment so that welding was done under still air conditions. Smoke tests were conducted to verify the existence of such conditions. During welding, the fumes rose vertically toward the ceiling; however, they billowed and drifted randomly about the welder's helmet as welding progressed.

The controls for this area could be adjusted to produce relative humidities ranging from less than 20 to more than 95 percent. Samples were collected under the following easily obtainable conditions of relative humidity:

- (1) Low (23 to 25 percent R.H.)
- (2) Medium (51 to 53 percent R.H.)
- (3) High (>95 percent R.H.)

Experimental Procedures

Welding. Conditions for welding with E70S-3 and E70T-4 electrodes were established in accordance with recommendations from the electrode manufacturers as follows:

	E70S-3	E70T-4
Current, A	320-330	550
Voltage, V	31-32	33
Wire feed rate, in./min (mm/s)	400-425 (169-180)	230 (97)
Shielding gas	Ar-2 O ₂	—
Shielding gas flow rate, ft ³ /h (liters/m)	40 (18.88)	—
Contact tube-to-work distance, in. (mm)	3/4 (19)	2-3/4 (70)
Travel speed, in./min (mm/s)	~20 (8.5)	~20 (8.5)
Polarity	Electrode positive	Electrode positive

Sampling. Sampling was conducted in the manner detailed in the previously referenced working document. Sampling was done at a location 13-1/2 in. (0.34 m) above and 12 in. (0.30 m) away from the arc. Some variations in this position occurred as the welder shifted his position to make adjustments and ease discomfort during periods of continuous welding. These movements affected the specific location of the helmet and lapel filter holders with respect to the fume stream; however, the orientation of one holder with respect to the other remained constant.

The filters were weighed on an analytical balance capable of weighing to 0.001 mg. This balance was located in a temperature and humidity controlled area in a building adjacent to that in which sampling was done. The filters were kept in a desiccator in this area until they were required. The manner in which the filters were handled is outlined below.

(1) The filters were weighed, placed between watch glass covers, and put in a desiccator.

(2) The filters were transported to the sampling area in the desiccator, and only enough filters for the required tests were removed from the weighing area. The filters were removed from the watch glass covers with smooth-faced tweezers and placed in filter holders.

(3) After the fume samples were collected, the filters were removed from the holders and placed between the watch glass covers again and returned to the desiccator.

(4) The filters were returned to the weighing area,

desiccated overnight, and then weighed to determine the quantity of fume collected.⁹

Experimental Results

Results obtained during the sampling of fumes associated with E70T-4 and E70S-3 electrodes are shown in Tables 2.22 and 2.23, respectively. Calculated fume concentrations for individual sampling experiments are shown in these tables. Also included are averages of the results of tests performed with the same electrode, filter holder location, and humidity level. These averages are neither threshold limit values nor time-weighted averages.

The following comments are based on a review of the experimental data:

(1) For a given filter location and humidity level, the weight of fumes collected during welding with the E70T-4 electrode was generally a direct function of the sampling time. The variations that occurred can be attributed to the random manner in which the fumes billowed and drifted and to movements of the welder during welding. The dependence of fume weight on sampling time was less evident when fumes produced by the E70S-3 electrodes were collected.

(2) The quantity of fumes produced by each electrode must also be considered in addition to the behavior of the fume stream and possible movements of the welder during welding. Fume quantities associated with the E70S-3 electrode were very small and the fumes tended to drift mainly upward as they were produced. In contrast, large quantities of fumes were produced by the E70T-4 electrode. These fumes drifted outward and upward as they were produced. Thus, the filters were more likely to be exposed to a consistent quantity of fumes when the E70T-4 electrode was used for welding than when the E70S-3 electrode was used.

(3) It was expected that concentrations of fumes at the welder's lapel would be consistently larger than those behind the welder's helmet, but this was not always the case, particularly when the E70S-3 electrode was used. This is explained by considering the respective locations of the helmet and lapel filters and the fume characteristics of the E70S-3 and E70T-4 electrodes. Because of the orientation of the welder with respect to the arc, the lapel filter was located slightly lower and further from the arc than the helmet filter. As a result of their specific location with respect to the fume stream, the helmet and lapel filters were exposed to different amounts of fumes. In previous work at Battelle, large variations in fume concentrations were observed for quite small variations in the location of the filter.

(4) The humidity level in the welding area did not significantly affect the results when fumes produced by

the E70S-3 electrode were sampled. There was an appreciable increase in fume concentration with increasing humidity level for fumes produced by the E70T-4. The implications of this observation are discussed below.

Significant implications may be applied to evidence that the humidity level in the welding area had an apparent effect on fume concentrations associated with the E70T-4 electrode but not on those associated with the E70S-3 electrode. Among them are the following:

(1) Concentrations of fumes produced by E70T-4 electrodes (and possibly covered electrodes and other flux cored electrodes) may vary in accordance with the ambient humidity.

(2) Gravimetric analyses of fumes produced by such electrodes may not produce valid results unless humidity effects are taken into account.

Fume sample weight would be increased if atmospheric moisture is (a) absorbed (or adsorbed) by the filter, or the fume sample, or both; (b) chemically combined with constituents in the fumes; or (c) both absorbed and chemically combined. If increased fume sample weight was caused by the absorption of moisture, a valid weight could be obtained by desiccating or vacuum drying the sample to remove absorbed moisture. These procedures would be ineffective if moisture was chemically combined with one or more fume constituents. The data tend to favor absorption as shown by these results:

(1) Five filters used to collect fumes produced by the E70S-3 electrode under high humidity conditions (>95 percent R.H.) were weighed immediately after use and again after overnight desiccating. A weight loss averaging 14 μg was observed between weighing periods. Presumably, this weight loss represented moisture absorbed by the filter and fume sample during the sampling interval and subsequently removed by the desiccant. In this instance, absorption appeared to be a reasonable cause for moisture pickup.

(2) Two filters used to collect fumes produced by the E70T-4 electrode under the same high humidity conditions were handled in the same manner, and a weight gain of 7 to 8 μg was observed. This implies that additional moisture was absorbed by the fume sample during desiccation; e.g., some constituent in the fume sample was a better desiccant than the one being used in the desiccator (anhydrous calcium sulfate). The results do not shed any light on the possible presence of water that is chemically combined with a fume constituent. In this case, however, chemical combination of water with one or more flux constituents appears possible.

To resolve this problem, samples of the fumes produced by E70T-4 electrodes were collected under high and medium humidity conditions. These samples were collected directly in the fume stream at a constant distance above the arc. The fume samples were weighed immediately after collection and after various conditioning treatments (desiccating, vacuum drying, etc.) to detect the presence (or absence) of absorbed moisture. The samples were also analyzed using a thermal gravi-

9. Several filters used to sample fumes under high humidity conditions (>95 percent R.H.) were weighed immediately after sampling and before desiccating. These filters were weighed again after overnight desiccating to determine if moisture was picked up during sampling.

Table 2.22
Fume sampling results with E70T-4 electrode

Filter location	Relative humidity, %	Fume wgt., mg	Sampling time, min.	Concentration, ¹ mg/m ³	Average concentration, mg/m ³
Helmet	23-25	0.624	30	11.1	13.6
	23-25	0.292	10	15.7	
	23-25	0.157	6	14.0	
Lapel	23-25	1.621	30	22.9	34.8
	23-25	0.959	10	40.8	
	23-25	0.577	6	40.9	
Helmet ²	51-53	1.555	30	27.9	31.4
	51-53	0.438	6.75	34.9	
	51-53	1.398	24	31.3	
Lapel ²	51-53	0.307	5.5	30.0	30.2
	51-53	0.578	10	31.1	
	51-53	0.682	12	30.5	
Helmet	95	1.072	12	48.0	51.9
	95	0.628	6	68.3	
	95	0.881	12	39.5	
Lapel	95	1.755	12	62.2	57.1
	95	0.762	6	54.0	
	95	1.553	12	55.1	

1. Concentrations are not time-weighted averages.

2. The Bendix pump was used to collect all samples under medium humidity conditions. For low and high humidity conditions, the Bendix pump was used to collect the helmet samples and the MSA pump was used to collect the lapel samples.

metric procedure capable of detecting the presence of chemically combined water.

Thermal Gravimetric Studies. Thermal gravimetric analysis (TGA) is a technique that is well-suited to detecting the temperatures at which absorbed and combined moisture is released by various materials. The equipment incorporates a sensitive balance that can detect weight changes in the microgram range when a sample is heated at a constant rate.

The samples for thermal gravimetric analysis were collected with Gelman DM Metrical filters, 37 mm in diameter with a pore size of 0.8 micron. Positioning the filter in the fume stream about 20 in. (0.51 m) above the arc permitted collection of a large fume sample within a reasonable welding time. Sampling was done at a rate of 2.5 to 3.0 liters/minute. Samples of E70T-4 fumes were collected when the humidity in the welding area while sampling was either greater than 95 percent or about 40 percent.

Thermal gravimetric analyses of the fume samples were conducted using a heating rate of 10°C/min. The results of individual analyses are discussed below:

(1) Initial attempts to analyze the entire sample

(filter plus fume sample) were not successful because decomposition of the filter masked the weight loss from the fume sample.

(2) Analyses of the fume samples (obtained by scraping the fume deposit from the filter) produced positive results (Fig. 2.20). The sample collected at greater than 95 percent relative humidity had several well-defined temperature ranges over which significant weight losses were observed. The sample collected at 40 percent humidity also lost weight but at a more gradual rate. Both samples experienced about a 0.8 percent weight loss at 100°C due to absorbed (or adsorbed) moisture on the fume particles. The sample collected under high humidity conditions lost weight sporadically as the temperature increased. The sample collected at 40 percent lost weight uniformly in these regions. Presumably, these weight loss patterns are associated with the volatilization of moisture combined with different compounds in the fume sample.

Of particular note was the fact that there was little difference in the magnitude of the total weight loss over the temperature range examined, regardless of the humidity at which the samples were collected; 3.3 percent

Table 2.23
Fume sampling results with E70S-3 electrode

Filter location	Relative humidity, %	Fume wgt., mg	Sampling time, min.	Concentration, ¹ mg/m ³	Average concentration, mg/m ³
Helmet	23-25	0.531	26.5	10.8	5.7
	23-25	0.249	30	4.5	
	23-25	0.084	26	1.7	
Lapel	23-25	0.437	26.5	7.0	3.9
	23-25	0.230	30	3.3	
	23-25	0.087	26	1.4	
Helmet	51-53	0.219	30	3.9	3.7
	51-53	0.163	27.5	3.2	
	51-53	0.118	16	3.9	
Lapel	51-53	0.254	30	3.6	3.2
	51-53	0.176	27.5	2.7	
	51-53	Note 2.	---	---	
Helmet	95	0.116	15	4.2	3.2
	95	0.058	15	2.1	
	95	Note 3.	---	---	
Lapel	95	0.364	15	10.3	6.8
	95	0.158	15	4.5	
	95	0.216	16.5	5.6	

1. Not time-weighted averages.

2. No sample reported, filter holder leaked.

3. No sample reported, moisture condensed in flowmeter tube.

for the sample collected at 95 percent humidity as opposed to 2.9 percent for the one collected at 40 percent humidity. If a fume sample collected at 20 to 25 percent relative humidity were analyzed by this technique, it is expected that the weight loss curve would resemble that obtained with the sample collected at 40 percent humidity, but the total weight loss would be less.

Discussion of Results. The results of this investigation indicate that the humidity in the welding area does not affect the weight of the fume samples; however, the amount of moisture picked up by absorption (or adsorption) and by combination with one or more constituents of the fumes is small (about 3 percent). Errors of this magnitude should have little bearing on the validity of gravimetric fume sampling results.

While the weight loss data obtained by thermal gravimetric analyses indicated that moisture was picked up by the fume sample, the amount of moisture detected was not large enough to explain the observed increase in the weight of E70T-4 fume samples as the relative humidity in the welding area increased. The thermal gravimetric data appeared to be valid, because comparable weight losses were observed independently by a member

of the AWS Subcommittee on Sampling when fume samples were heated to 1200°F (649°C).

Other factors that may contribute to the observed increase of E70T-4 fume weights with increasing relative humidity are the effects of humidity on the (a) fume generation rate, (b) fume composition, (c) collection efficiency of the filter, and (d) the electrostatic attraction between particles. These factors were not examined during the course of the research program.

Summary of Part II

Principal Fumes and Gases Present

From the literature (Ref. 2.20), ranges for the major constituents in the fumes produced by four typical Scandinavian covered electrodes are as listed below. Three of these electrodes appear to have been low hydrogen electrodes with iron powder additions (individual results in Table 2.4).

Particle	Range, wt. %
Fe ₂ O ₃	25 to 44
SiO ₂	7 to 30
K ₂ O	7 to 24
F ⁻	0 to 20
Na ₂ O	2 to 17
CaO	0 to 16
MnO	5 to 10
TiO ₂	0.2 to 2
MgO	0.1 to 1
Al ₂ O ₃	0 to 0.6
ZrO ₂	0 to 0.6
ZnO	0.02 to 0.09
Cu	0.03 to 0.07
Pb	0.02 to 0.05
Cr	0.01 to 0.04

tion assumes that the elements detected were completely converted to oxides.

Element	Oxide	Range, wt. %	
		E7024	E410
Fe	Fe ₂ O ₃	28 to 43	14 to 29
Si	SiO ₂	8 to 31	3 to 5
K	K ₂ O	10 to 14	12 to 24
Na	Na ₂ O	4 to 8	5 to 11
Mn	MnO ₂	3 to 6	2 to 3
Ca	CaO	0.1	3 to 6
Zn	ZnO	0.1	0.1
Ti	TiO ₂	0.5 to 0.8	0.7
Al	Al ₂ O ₃	0.1 to 0.2	0.9
Cr	—	0.01	5 to 10
(Total oxides)		(89 to 103)	(47 to 90)

In the present study the major constituents in the fumes produced by one E410-16 and two E7024 covered electrodes were determined by optical emission spectroscopy to be as follows (complete data in Table 2.5). The tabula-

From the literature (Ref. 2.3), the elemental compositions of fumes produced by typical E70T-1, E70T-4, and E70T-5 electrodes, assuming an oxide form of these fumes, have been reported as follows:

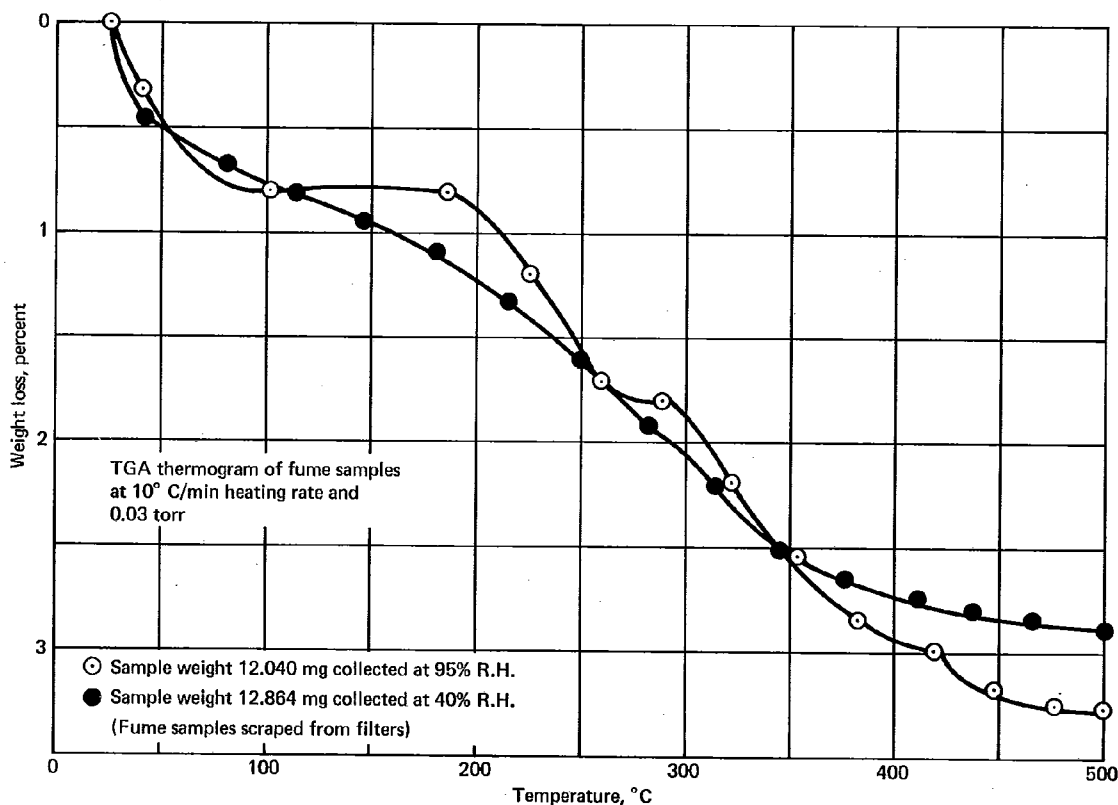


Fig. 2.20—Thermal gravimetric analysis of fume samples from E70T-4 steel electrodes

110/FUMES AND GASES

Element	Oxide	Composition, oxide weight %		
		E70T-1 Rutile- base	E70T-4 Fluorspar- base	E70T-5 Silicon- base
Fe	Fe ₂ O ₃	40	19	33
Mn	MnO ₂	8	3	6
Si	SiO ₂	39	6	31
Ca	CaO	—	18	11
Ti	TiO ₂	3	—	—
Mg	MgO	5	15	—
Al	Al ₂ O ₃	—	17	—
F	F ⁻	7	13	7
Totals		102	91	87

In this study, the fumes from three flux covered electrodes were identified by optical emission spectroscopy to have the compositions that are listed below. The E70T-1 and E70T-5 electrodes studied in this program appear to have differed considerably (at least in silica content) from those reported above from the literature, while the E70T-4 electrode seems to have had an alumina-and-fluorspar flux similar to that reported above (see also Table 2.10).

Element	Oxide	Range, oxide weight %		
		E70T-1	E70T-4	E70T-5
Fe	Fe ₂ O ₃	43 to 57	21 to 36	43 to 57
Mn	MnO ₂	6 to 10	3 to 5	6 to 10
Si	SiO ₂	3 to 5	0.2	3 to 5
Ca	CaO	0.1	21 to 35	11 to 17
Ti	TiO ₂	0.8	0.2	0.3
Mg	MgO	0.03	12 to 17	0.3
Al	Al ₂ O ₃	0.8	13 to 19	2 to 4
Na	Na ₂ O	5 to 8	0.1	1
K	K ₂ O	1	2	5 to 7
Zn	ZnO	0.1	0.1	0.1
Total		58 to 80	72 to 114	71 to 101

Figures and short tables are used throughout this report to summarize the data and assist in the interpretation of the results. Data on the fume generation characteristics of specific arc welding electrodes are presented in detailed tabular form in Appendix B. These tables contain information on (a) the conditions under which the experimental data were obtained, (b) the melting and metal deposition rates of the electrode, and (c) calculated quantities that relate the amount of fumes produced during welding to the metal deposition rate and other electrode characteristics.

Fume generation rates have been expressed in "measured" and "normalized" values. The normalized value minimizes the effects of unintentional variations in welding current on fume generation rate. Normalization was accomplished by relating the fume generation rate to the current squared. The current squared normalization will fit a wide variety of fume generation data.

The fume generation rate can be used effectively by welding engineers, industrial hygienists, ventilation specialists, and others. The calculated factor "weight of

fumes per unit weight of deposited metal" approximates the amount of fumes produced during production welding operations. The factor compares welding processes on the basis of fumes produced per weight of deposited metal.

Covered Electrodes

Fume Generation Characteristics. Generation rates and fume ratios of carbon steel, low alloy steel, stainless steel, nickel, and other high alloy covered electrodes are shown in bar graphs in Fig. 2.6.

The data in Fig. 2.6 must be interpreted carefully. They were obtained by evaluating 4 mm (5/32 in.) diameter electrodes from various producers under conditions recommended by the manufacturers. Data differing from those shown will be obtained if the electrode diameter or welding conditions are changed.

Fume generation rates and ratios of weight of fume to weight of deposited metal were somewhat higher for E6010 electrodes than for the other covered electrodes. The E7024 electrode rates were comparable to those of other carbon and low alloy steel electrodes. The ratios of fume to weight of deposited metal for E7024 electrodes were lower than those of other electrodes. This results from the combination of a relatively low fume generation rate and the high deposition rate contributed by the iron powder (up to 50 percent) in the coverings.

Fume generation rate ranges for stainless steel, nickel, and other high alloy covered electrodes were similar in magnitude; ranges for ratios of weight of fumes to weight of deposited metal generally overlapped one another.

Fume Composition. Data for the major elements in the fumes (e.g. iron, manganese, and silicon for carbon steel electrodes) and fluorides produced by covered (and other) electrodes are presented in Table 2.18. The analytical data do not total 100 percent, principally because the limited studies did not include detection of fume constituents originating from the electrode covering.

Major constituents in the fumes produced by E7024 and E410-16 covered electrodes are shown in Table 2.5.

Flux-Cored Electrodes

Fume Generation Characteristics. Ranges of (a) fume generation rates and (b) ratios of weight of fumes to weight of deposited metal for representative carbon steel, low alloy steel, and stainless steel flux cored electrodes are shown in Fig. 2.7. The data upon which Fig. 2.7 is based are summarized in Table 2.2.

E70T-1 Electrodes. The ranges of fume generation and ratios of weight of fumes to weight of deposited metal were broadest for this classification of electrodes. The electrode with the highest fume generation rate contained appreciable amounts of fluorides (Table 2.18); such compounds are known to enhance the production of fumes.

E70T-4 Electrodes. High fume generation rates were experienced with the self-shielded E70T-4 electrodes. Profuse fume generation is shown for an E70T-4 elec-

trode made several years ago that is no longer available on the market. Since another currently available electrode made by the same producer had a much lower fume generation rate, it appears that changes in the electrode flux have been made to reduce fume quantities.

E70T-5 Electrodes. The highest fume generation rates were encountered with E70T-5 electrodes; the E70T-5 electrodes can be used with or without a shielding gas, and the basic type flux contains ingredients that produce large amounts of gas and fumes. Ratios of fume weight to weight of deposited metal were highest for these electrodes also.

Low Alloy Steel Electrodes. The fumes generated by 81-C3 and 91-B3 low alloy steel electrodes were low compared to those produced by carbon steel flux cored electrodes. A similar comparison holds for carbon steel and low alloy steel covered electrodes.

Stainless Steel Electrodes. The fumes generated by three self-shielded stainless steel electrodes varied widely; this characteristic appears to be flux-related.

Effect of Shielding Gas. Fume generation rates can be affected by the type of shielding gas used during welding. The data summarized in Table 2.24 show a reduction of 15 to 25 percent in fume generation rates when Ar-25 CO₂ shielding is used instead of CO₂. The argon-based shielding gas has a lower oxidation potential than CO₂, and oxidation processes contributing to the formation of fumes at and near the tip of the electrode are consequently decreased. The metal deposition rates for these electrodes are unaffected by the type of gas shielding used. Thus, the ratio of weight of fumes to weight of deposited metal are also smaller when Ar-25 CO₂ is used for shielding.

Fume Composition. The composition of fumes produced by flux cored electrodes is determined by the compositions of the electrode sheath, flux core, and (to a minor extent) base metal. Since the composition of the sheath varies but little from producer to producer, variations in fume compositions for such electrodes are mostly caused by differences in the flux core ingredients.

The constituents that may be detected in flux cores and slags associated with representative flux cored electrodes are shown in Tables 2.7 and 2.8. Most of these flux constituents will be present as elements and compounds in the fumes produced by electrodes incorporating them. The proportions will differ because some constituents are transferred by the arc to the slag or to the weld metal. Elemental compositions of the fumes and postulated oxides produced by typical E70T-1, E70T-4, and E70T-5 electrodes are shown in Table 2.9.

Fume compositions determined by optical emission spectroscopy are shown in Table 2.10.

Solid Electrodes

Fume Generation Characteristics. The fume generation characteristics of solid electrodes and rods used for gas metal arc welding and gas tungsten arc welding are a

direct function of the amount of electrode consumed during welding, modified by the type of shielding gas, the metal transfer characteristics of the arc, and the welding conditions.

Gas Metal Arc Electrodes. Fume generation characteristics for carbon steel, stainless steel, high alloy, copper, and aluminum gas metal arc welding electrodes are shown in Fig. 2.8.

Steel Electrodes. The fume generation characteristics of steel electrodes made by three different manufacturers are shown for spray transfer with Ar-2 O₂ or Ar-9 CO₂ shielding, globular transfer with CO₂ shielding, and short circuiting transfer with Ar-25 CO₂ shielding. There was little variation in composition. A single E70S-5 electrode was also evaluated in the same transfer modes.

Other Solid Electrodes. Representative stainless steel, high alloy, copper, and aluminum solid electrodes were investigated under spray transfer conditions. The data in Fig. 2.8 show strong dependency on welding current and other process variables.

High Alloy Electrodes. Four high alloy electrodes (one stainless steel electrode, two nickel-base electrodes, and one cobalt-base electrode) had fume generation rates and ratios of weight of fumes to weight of deposited metal well below those of carbon steel electrodes. A third nickel-base electrode had a fume generation rate approaching those of the carbon steel electrodes. It was a small diameter electrode; therefore, the current density was high and the higher arc temperature produced more fumes.

Aluminum Electrodes. The aluminum electrodes varied in performance. The ER4043 electrode produced fumes at low rates with a low ratio of weight of fumes to weight of deposited metal. The ER5356 electrode produced fumes at much higher rates. Both electrodes had much higher fume generation rates at longer contact tube-to-work distances with evidence of lack of shielding of the arc and weld pool. Good shielding and careful control of the welding torch setup are needed to minimize fumes, resulting in the production of high quality welded joints as an added benefit.

Copper Electrodes. Fume generation rates and ratios of weight of fumes to weight of deposited metal for an ERCu and an ERCuA1-A2 electrode were comparable in magnitude to those associated with carbon steel electrodes.

Fume Compositions. The composition of the fumes produced by solid gas metal arc welding electrodes is controlled by the composition of the electrode and any coating that might be on the electrode surface. Each of the fume samples contained iron, manganese, silicon, and copper (or their oxides).

Because of its low threshold limit value, there is more concern about the presence of copper fume in the welding environment than about iron oxide fume. Table 2.12 combines data on the baseline fume generation rates of three E70S-3 electrodes with the compositional data on the fumes. The ACGIH time-weighted average threshold limit value for iron oxide fumes (5 mg/m³) is 25 times as large as that for copper fumes (0.2 mg/m³). However,

the results of the experimental studies indicate that the iron oxide fume generation rates for the E70S-3 (54), E70S-3 (57), and E70S-3 (58) electrodes were 925, 154, and 89 times as great, respectively, as the copper fume generation rates. Thus, when welding with these electrodes, the allowable limit for iron oxide fumes would be exceeded long before reaching the limit for copper fumes.

Compositions of the fumes produced by the gas metal arc electrodes used for welding other base metals (stainless steels, nickel-base alloys, etc.) are determined by the composition of the respective electrodes.

Fume Generation Characteristics of Gas Tungsten Arc Welding Rods

The fume generation rates for an E308L stainless steel filler rod and a 5356 aluminum filler rod were a small fraction of the rates associated with other processes investigated during this program.

Process Variables

Some of the variables affecting fume production are:

- (1) Welding process (summarized above)
- (2) Current
- (3) Voltage
- (4) Electrode polarity
- (5) Shielding gas (flux cored and solid electrodes)
- (6) Contact tube-to-work distance (flux cored and solid electrodes)
- (7) Metal transfer mode
- (8) Electrode characteristics (manufacturer, diameter, core wire composition, covering or flux composition, etc.)

Current Effects. Fume generation rate, as shown in Fig. 2.9 (based on Tables B26 and B27), varies nonlinearly with current. Studies to fit the data to a power function indicated that the fume generation rate (FGR) relation to current was different for each type of electrode. The simplest regression equation seems to be.

$$FGR = aI^2$$

where a is a constant and I is the current.

Current Density Effects. Current density also has a bearing on the rate at which fumes are produced.

Variable Current Density. The fume generation characteristics of three E6013 electrodes, all made by the same producer, are shown in Fig. 2.10.

The fume generation rate increased with current density in what appears to be a parabolic relation. With direct current, the fume generation rate is higher with electrode positive than that observed with electrode negative because the electrode is heated to higher temperatures when the anode spot is on the electrode.

Constant Current Density. The fume generation characteristics of four E7018 electrodes are shown in Figs.

2.11 and 2.12. The fume generation rate (Fig. 2.10) and the electrode melting rate (Table B32) were approximately proportional to the square of the diameter. The amount of fumes produced during welding was largely dependent upon the amount of electrode consumed. Fig. 2.12 shows the dependence of fume generation rate on welding current. With approximately equal current densities in each electrode, the variation of fume generation rate with current was almost linear.

Arc Voltage-Arc Length Effects. Arc voltage and arc length are closely related welding variables. The fume generation characteristics of selected electrodes increased with increasing arc length for all of the electrodes included in this investigation.

Contact Tube-To-Work Distance Effects. The distance between the end of the contact tube and the surface of the base plate affects the melting and metal deposition rates in flux cored arc welding and gas metal arc welding. The fume generation characteristics of an E70T-1 flux cored electrode were determined as a function of contact tube-to-work distance. Two current levels were studied with the following results:

(1) At each of the current levels there was a gradual increase in metal deposition rate with increasing contact tube-to-work distance (Tables B42 and B43). When the contact tube-to-work distance increases, the wire feed rate must be increased to maintain a constant current level. The increased melting rate is accompanied by a higher deposition rate.

(2) For each current level, the fume generation rate remained essentially constant for each contact tube-to-work distance.

(3) The ratio of weight of fumes to weight of deposited metal decreased gradually with increasing contact tube-to-work distance.

(4) The effect of current on fume generation rate is evident in Fig. 2.15. At 450 A, the fume generation rate was about 1 g/min.; at 520 A, the rate was 1.3 g/min.

Shielding Gas Effects. The shielding gas in flux cored and gas metal arc welding affects (a) the rate at which fumes are produced during welding, and (b) the composition of the fumes. Copper contents in the fumes appeared to be less a function of the shielding gas than were the other core wire elements and their oxides.

Metal Transfer Mode. The effects of shielding gas type on the composition of the fumes produced by E70S-3 gas metal arc electrodes used for welding carbon steels were evaluated using welding conditions to produce the following transfer modes: (a) spray transfer with Ar-2 O₂ shielding, (b) spray transfer with Ar-9 CO₂ shielding, and (c) globular transfer with CO₂ shielding. The fume samples were collected on cellulose membrane filters and analyzed by atomic absorption procedures. The resulting data plus the calculated weight percentages of each oxide are shown in Table 2.14. The apparent trends were these:

(1) Iron (iron oxide) contents were highest in the spray transfer mode with either Ar-2 O₂ or Ar-9 CO₂

shielding and lowest in the globular transfer mode with CO₂ shielding. These results are in agreement with those of Heile and Hill (Ref. 2.3).

(2) Manganese (manganese oxide) contents were highest in either the spray transfer mode with Ar-9 CO₂ shielding or in the globular transfer mode with CO₂ shielding; the Mn (or MnO₂) content was lowest in the spray transfer mode with Ar-2 O₂ shielding. Here, the oxidation potential of the shielding gas had a slight effect on the contents of manganese (manganese oxide) in the fumes.

(3) Silicon (silicon dioxide) contents were highest in the globular transfer mode with an oxidizing gas, CO₂. These results are also in agreement with those of Heile and Hill (Ref. 2.3). There is no apparent explanation for the low silicon contents in the fumes produced by electrodes 54 and 57.

Effects of Iron Powder Additions. The fume generation characteristics of two groups of mild steel iron powder electrodes are summarized in Table 2.15.

High-Titania Electrodes. At the measured welding current, the fume generation rates for E6013, E7014, and E7024 electrodes are similar in magnitude (0.68 to 0.72 g/min.) and appear unaffected by the presence or absence of iron powder additions to the electrode coverings. Rates normalized to a current of 175 A varied inversely with the amount of iron powder in the electrode covering.

The ratio of the weight of fumes to weight of deposited metal also varied inversely with the amount of iron powder in the covering when these electrodes were used at recommended current levels. The E7024 electrode had the lowest ratio because its fume generation rate was low and its metal deposition rate was high.

Low Hydrogen Electrodes. At recommended current levels, the fume generation rates for E7016 (no iron powder addition) and E7018 (moderate iron powder addition) electrodes were almost identical; the rate for an E7028 electrode (high iron powder addition) was twice as large. The normalized rates for these electrodes were similar in magnitude (0.50 to 0.58 g/min.). The rates at which fumes were produced appeared to be controlled by ingredients other than iron powder in the electrode covering. Calcium fluoride, a compound common to these low hydrogen electrodes, probably exerted a controlling influence on the rate at which fumes were produced.

Ratios of weight of fumes to weight of deposited metal for these electrodes were similar.

Other Studies

Electrode Angle Effects. The effect of electrode angle on the rate at which fumes are produced by covered electrodes was studied at angles of 30, 60, and 90 degrees to the workpiece; a tubular guide was used to establish and maintain the desired electrode angle. Bead-on-plate welds were deposited with each electrode at a nominal current of 150 A. The results are shown in Fig. 2.16.

The fume generation rate gradually decreased as the angle between the electrode and workpiece increased to-

ward 90 degrees. Care should be observed in interpreting these data strictly in terms of an electrode angle effect because a lengthening of the arc probably occurred as the electrode angle decreased. Fume generation rates are affected substantially by changes in arc length.

Base Plate Effects. Fume generation characteristics for covered, flux cored, and solid electrodes were determined with a base plate having composition similar to that of the core wire or sheath. These studies included fume samples for gravimetric and chemical analyses collected from stainless steel bead-on-plate welds deposited on carbon and stainless steel plate. The experimental results are summarized in Tables 2.16 and 2.17 and as follows:

(1) **Fume Generation Characteristics.** Fume Generation rates and ratio of weight of fumes to weight of deposited metal were unaffected by the type of base metal used during welding.

(2) **Fume Composition.** The composition of the fumes did reflect the composition of the base metal upon which the welds were deposited as well as that of the electrode. On stainless steel, the fumes from an E316-16 electrode contained higher contents of manganese, nickel, and chromium than they did when that electrode was used on carbon steel (Table 2.17). It is concluded that electrode and base plate should be matched if fume compositions are to be determined.

Diameter Effects with Flux Cored Electrodes. The measured fume generation rate for a small diameter electrode is less than that for a large diameter electrode. However, if the fume generation rates are normalized to a common current, the data indicate that more fumes will be produced by the small diameter electrode than by the large diameter electrode at the same current level. Fume generation rates are dependent upon the rate at which the electrode is consumed. At the same current level, the melting rate for the smaller of the two electrodes will be greater than that for the larger because of the greater current density in the small diameter electrode and the effect of increased I^2R heating in the smaller electrode.

Analytical Studies

Optical emission spectroscopy yields a wealth of analytical data because 70 or more elements can be detected simultaneously and their content can be estimated on a semiquantitative basis. This method provides an overview of most of the elements present in the fume sample, regardless of their origin; i.e., from the core wire (sheath), electrode covering (flux), or flux plate.

Atomic absorption analysis is also capable of determining the presence of about 70 elements, but each element must be detected individually. This method is better-suited for the detection of elements present in large amounts and the detection accuracy is excellent. This method, combined with optical emission spectroscopy, provides reliable data on fume sample compositions.

Classical chemical analysis procedures are most useful

in determining constituents whose presence cannot be detected by optical emission spectroscopy or atomic absorption analysis (e.g., fluorides, chlorides, gases, etc.).

Analysis of Fume. In this study, AA analysis was used to detect only the major constituents that originated in the core wire or electrode sheath (i.e., iron, manganese, and silicon in the case of fumes produced by low carbon steel covered or flux cored electrodes). As a result, analytical data on fumes associated with covered or flux cored electrodes do not total 100 percent, because they do not include certain constituents originating in the electrode covering or flux (e.g., sodium, calcium, titanium, etc.).

To supplement these data, fluoride contents in the fumes produced by many of the low hydrogen electrodes were determined by wet chemical analysis.

Fume Characterization. The fumes produced by electrodes used for shielded metal arc welding (E7024 and E410-16) and flux cored arc welding (E70T-1, E70T-4, and E70T-5) were analyzed for elemental composition by optical emission spectroscopy (OES) and for crystalline phases by x-ray diffraction (XRD). Scanning electron microscopy (SEM) was used to study particle morphology. Semiquantitative results of the OES analysis of the fume samples are shown in Table 2.19.

Only one crystalline phase, iron oxide (Fe_3O_4 , magnetite), was detected by XRD in the fumes produced by the covered electrodes; manganese was probably present in this phase also since it can replace iron in the crystal lattice. Crystalline phases containing silicon were not detected; however, since silicon was detected in the fumes produced by the E7024 and E410-16 electrodes, it was probably present as a glassy SiO_2 phase along with potassium and sodium. The x-ray diffraction pattern from the fumes produced by the E410-16 electrode had an extra diffraction line whose presence was attributed to a chromium compound. The study did not determine the valence of chromium in chromium compounds detected in fume samples.

In the fumes produced by the flux cored electrodes, the major crystalline phase detected was Fe_3O_4 ; manganese was probably present in this phase also. In addition, a crystalline calcium fluoride phase (CaF_2 , fluorite) was detected in the fumes associated with E70T-4 and E70T-5 electrodes. Although magnesium was present as a major constituent in the fumes produced by the E70T-4 electrode, crystalline phases containing magnesium were not detected. Crystalline phases containing silicon were not detected.

Gas Detection. Studies to detect the presence (or absence) of selected gases (carbon monoxide and nitrogen dioxide) produced during arc welding operations were conducted using gas detector tubes.

Two gases, carbon monoxide and nitrogen dioxide, were of specific interest because they are frequently present during arc welding operations. Literature references (Refs. 2.22 and 2.23) also report ozone in the vicinity of arc welding processes.

Unless ventilation is provided, carbon monoxide (CO) may present a problem during welding with processes in which the arc is shielded by CO_2 or gas mixtures containing CO_2 ; e.g., flux cored arc welding and gas metal arc welding. Carbon monoxide in inconsequential amounts may also be present during shielded metal arc welding. In gas shielded welding operations, problems with carbon monoxide can be minimized by the use of argon or argon-based shielding gases ($\text{Ar}-2\text{O}_2$, $\text{Ar}-9\text{CO}_2$, etc.).

The data in Table 2.18 can be used to establish a relationship between the amount of carbon dioxide in the shielding gas and the amount of carbon monoxide in the welding atmosphere (Fig. 2.19). Carbon monoxide concentrations rose gradually as the amount of carbon dioxide in the shielding gas increased from 0 to 100 percent. Additional data would be needed to define this relationship more accurately.

Nitrogen dioxide is potentially a problem, based on published ACGIH threshold limit values, when welding is done with the arc shielded by argon or gas mixtures containing large amounts of argon (probably by interaction between excited argon atoms and nitrogen molecules that penetrated the gaseous shield). This study did not find nitrogen dioxide in the unshielded arc.

Effect of Humidity or Fume Sampling. The studies of fume sampling collected under low, medium, and high humidity conditions indicate that the humidity in the welding area does affect the weight of the fume samples; however, the amount of moisture picked up by absorption (or adsorption) and by combination with one or more constituents of the fumes is small (about three percent). Fume weights collected from E70T-4 welds increased with increasing relative humidity more than their measured moisture contents would explain. It is felt that other factors not studied in this program may contribute to this anomaly.