Fumes and Gases in the Welding Environment

A Research Report on Fumes and Gases Generated During Welding Operations

Research performed at Battelle-Columbus Laboratories under contract with the American Welding Society and supported by industry contributions

Under the direction of the AWS RESEARCH COMMITTEE ON SAFETY AND HEALTH

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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 operating 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

	E7018		E70T-1	
Parameter	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	Postive	Positive	Positive

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

	E7018				E70T-1			
	AWS Subcommittee on Sampling				AWS Subcommittee on Sampling			
Characteristics	A	B	C	Battelle	A	B	C	Battelle
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)

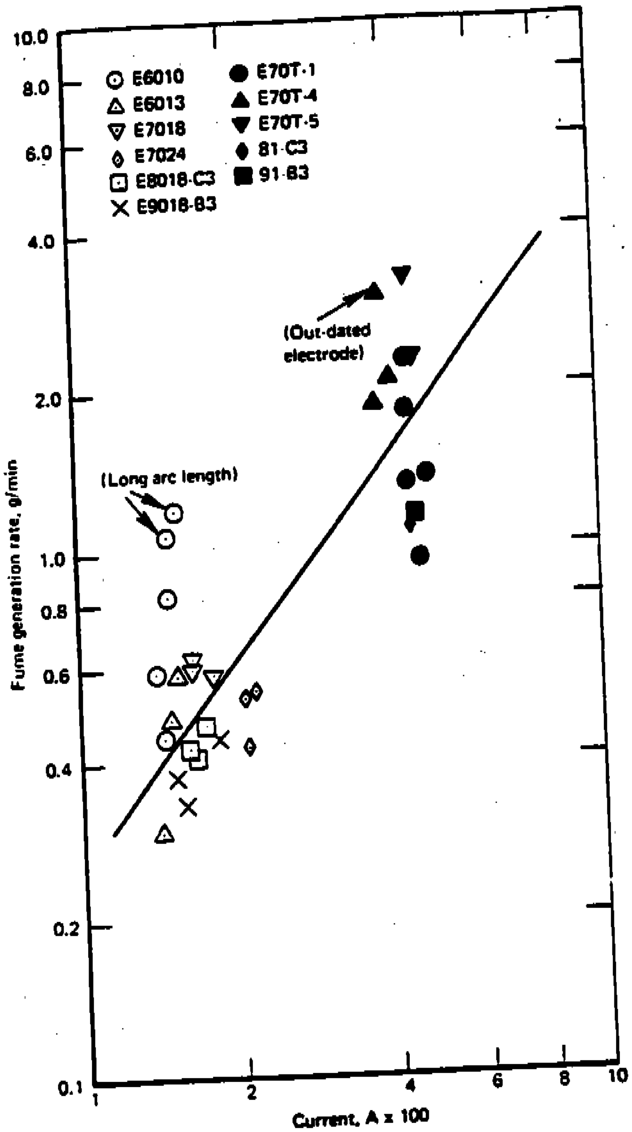

Fig. 2.2–Fume generation rates for covered and flux cored electrodes used for welding carbon and low alloy steels as a function of current

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 r^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

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

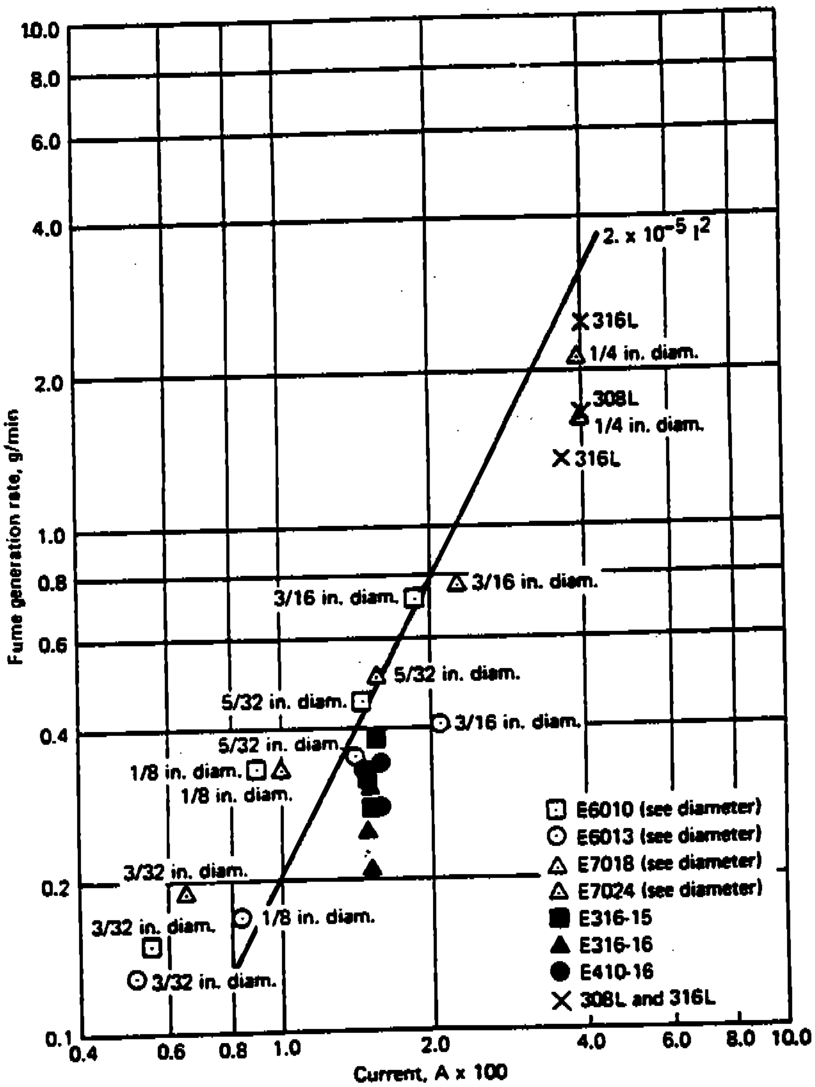

Fig. 2.3–Fume generation rates for carbon and stainless steel covered electrodes as a function of current

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

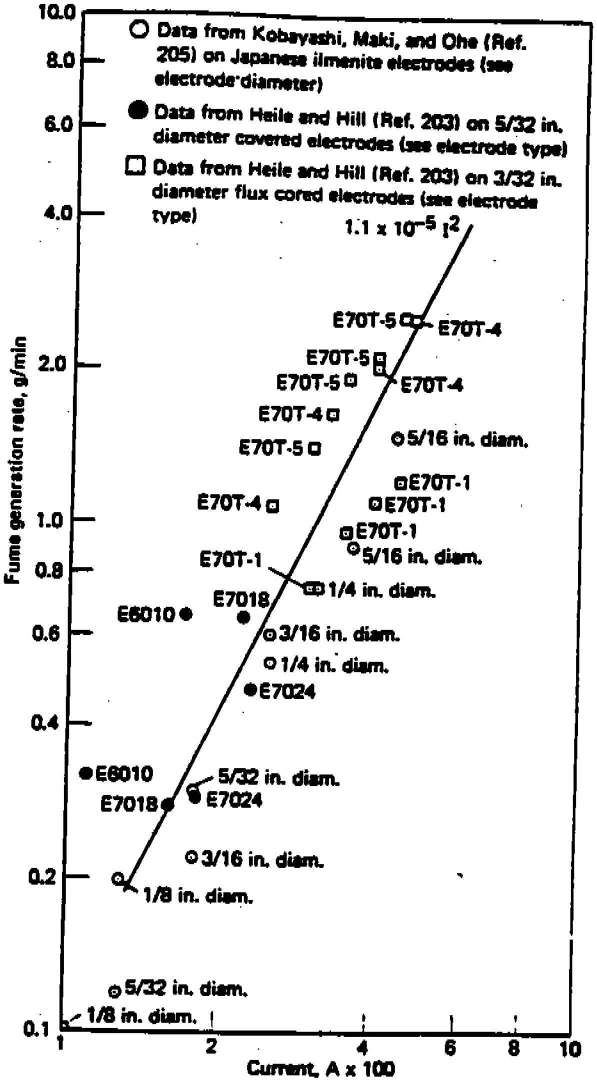

Fig. 2.4—Fume generation rates obtained by other investigators with carbon steel covered and flux cored electrodes as a function of current

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

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: Fume generation rate, g/min	Average range: Weight of fumes/weight of deposited metal, g/kg*	Source table-App. B
		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: Fume generation rate, g/min	Average range: Weight of fumes/weight of deposited metal, g/kg*	Source table-App. B
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 Al-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.

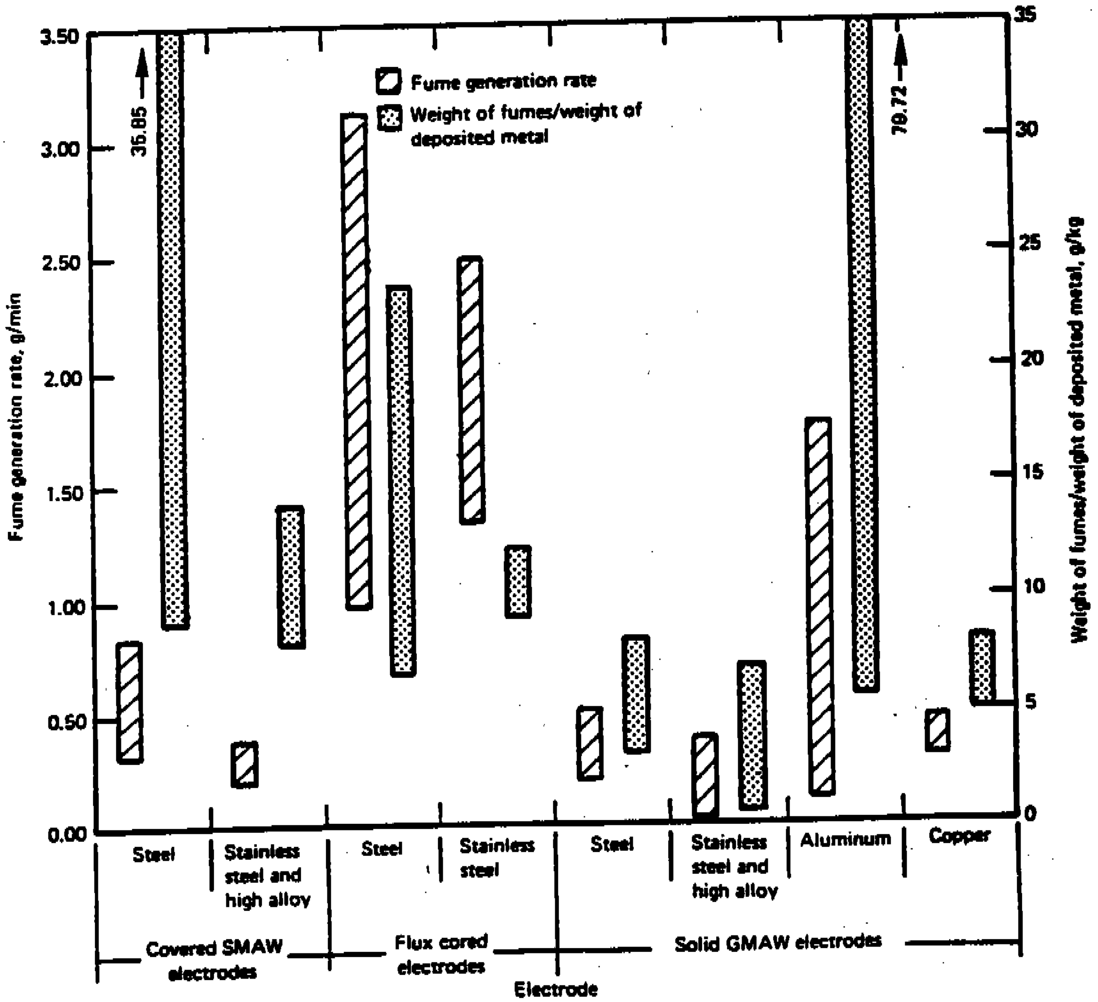

Fig. 2.5—Ranges of fume generation rates and ratios of weight of deposited metal for covered, flux cored, and solid GMAW electrodes

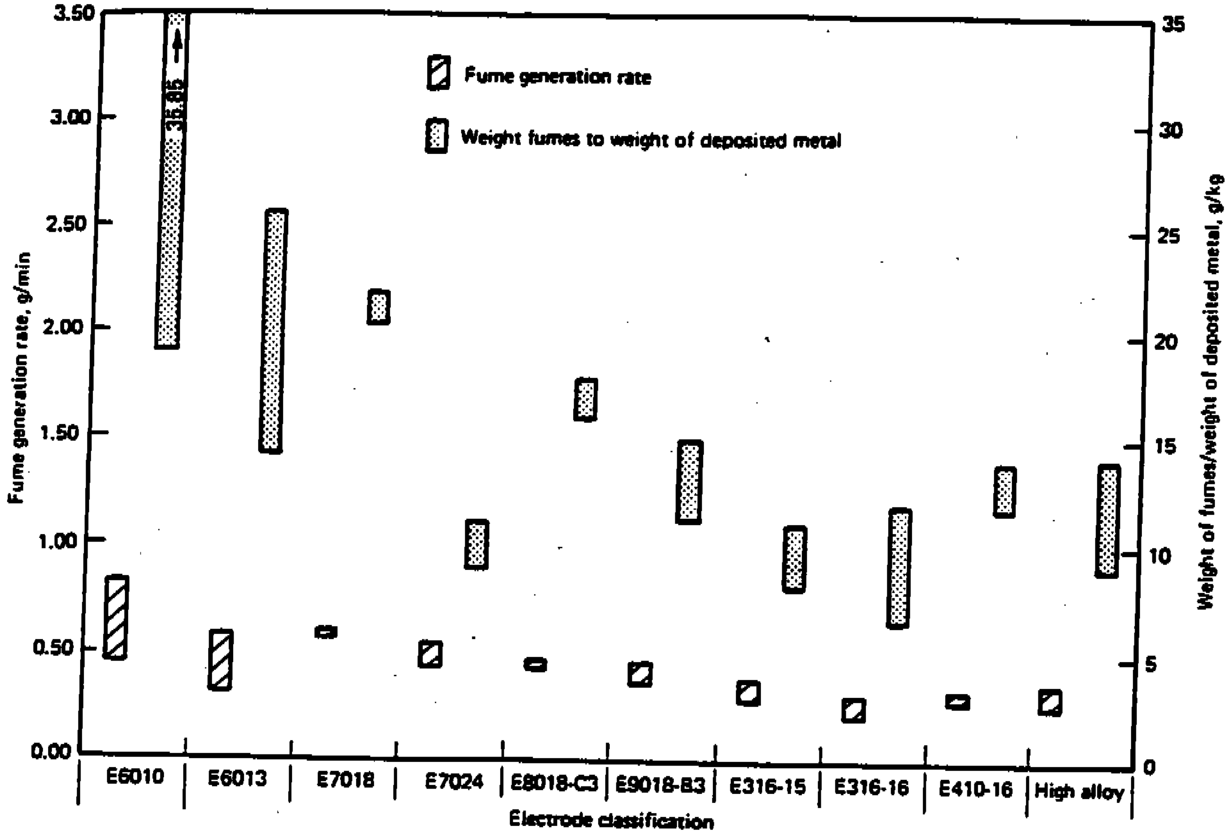

Fig. 2.6—Fume generation rates and ratios of weight of fumes to weight of deposited metal for covered electrodes

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_2O_3	2.0	5.9	1.0
CaF_2	...	...	27.0
CaO	...	1.6	...
MgO	6.0	2.6	...
Na_2O	8.0	1.1	1.4
K_2O	...	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_2O_3	25.5	24.5	36.5	43.5
Al_2O_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_2O	24.4	17.6	17.6	7.2
Na_2O	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	...

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 spectoscopic 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_2O_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_2O)	8-12 (9.6-14.4)	8-12 (9.6-14.4)	10-20 (12.0-24.0)
Na	(Na_2O)	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	(Z_nO)	<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_2O_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.

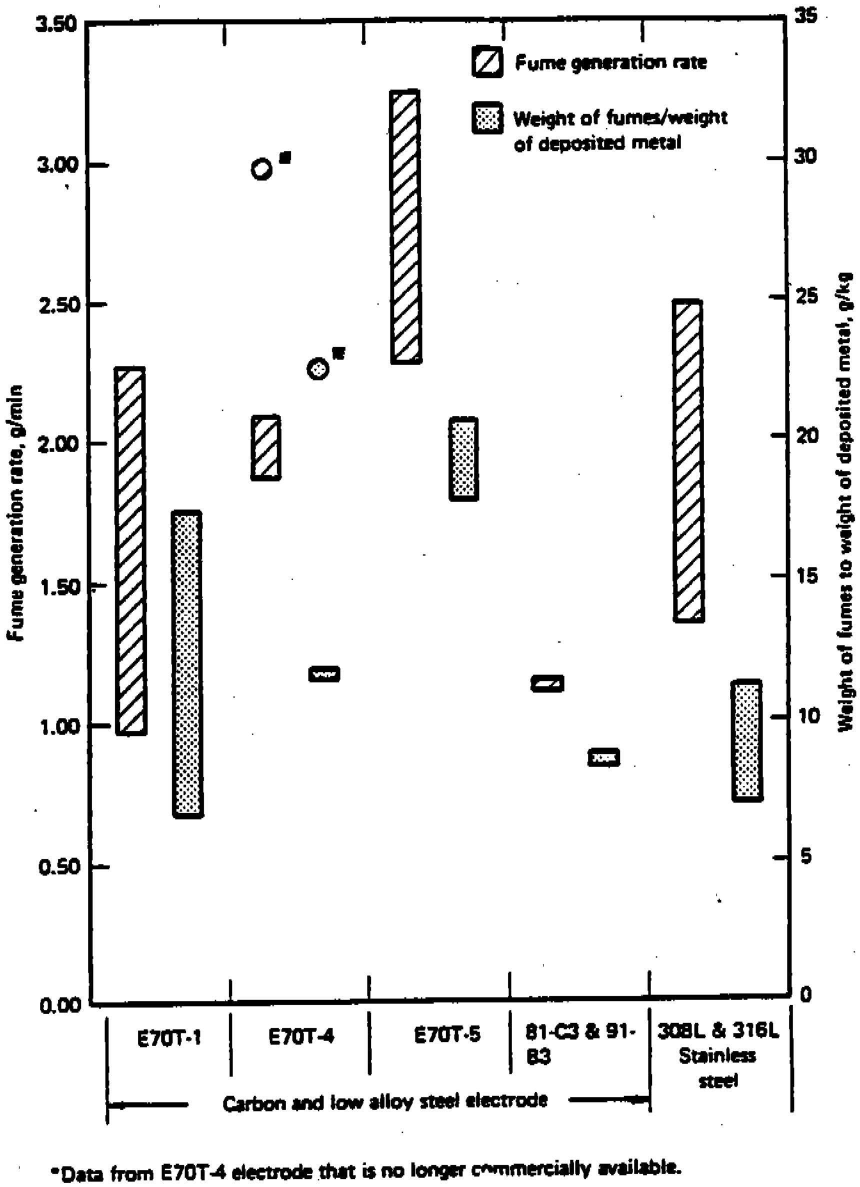

Fig. 2.7—Fume generation rates and ratios of weight of fumes to weight of deposited metal for flux cored electrodes

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 CO_2 is a convention used to designate a gas mixture of 25% CO_2, 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_2O_2	2.1	4.3	0.5
TiO_2	40.5	9.8	...
ZrO_2	...	6.2	...
CaO	0.7	9.7	3.2
Na_2O	1.6	1.9	...
K_2O	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 CO_2 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 CO_2 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 CO_2 shielding was used instead of CO_2. This is because the argon-based shielding gas has a lower oxidation potential than CO_2, 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 CO_2 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 CO_2 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)

	Composition, weight percent			
	Type 1	Type 2	Type 3	Type 4
Compound or element	Fluorspar-aluminum flux	Fluorspar-titania flux	Fluorspar-lime-titania flux	Fluorspar-lime flux
SiO_2	0.5	3.6	4.2	6.9
Al	15.4	1.9	1.4	...
Al_2O_3	...	...	...	0.6
TiO_2	...	20.6	14.7	1.2
CaO	...	...	4.0	3.2
MgO	12.6	4.5	2.2	...
K_2O	0.4	0.6	...	...
Na_2O	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

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 fu generation rates and ratios of weight of fume to wei of deposited metal associated with carbon steel, stainl steel, high alloy, copper, and aluminum gas metal welding electrodes investigated during this program shown in Fig. 2.8. The data upon which these rang are based are summarized in Table 2.2; detailed inform tion on the fume generation characteristics of individ electrodes are contained in Tables B16 to B24 along w the welding conditions.

(1) Steel Electrodes. The results obtained with c bon steel electrodes are reviewed separately from the obtained with other types of solid electrodes. Caution required in interpreting the data in Fig. 2.8 because the dependency of the fume generation characteristics welding current and other process variables. The fum generation characteristics of three 1.1 mm (0.045 in E70S-3 electrodes, each made by a different manufa turer, were determined at appropriate current levels i the following transfer modes: spray transfer with Ar-O_2 or Ar-9 CO_2 shielding; globular transfer with CC shielding; and short circuiting transfer with Ar-25 CC shielding. Although the electrodes were made by di ferent producers, there was little variation in composi tion. The thickness of the copper coating on the electrod surface varied from zero to several microinches. A singl E70S-5 electrode was also evaluated in various transfe modes: spray transfer with Ar-2 O_2 shielding; globula transfer with CO_2 shielding; and short circuiting transfe with Ar-25 CO_2 shielding.

Fume generation rates for the three E70S-3 electrode were similar in magnitude during spray transfer weldin with Ar-2 O_2 or AR-9 CO_2 shielding, and durin globular transfer welding with CO_2 shielding. Unde these conditions, the ratios of weight of fumes to weigh 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_2O_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_2O_3)	---		9	(17.0)	---	
F		7		13		7	

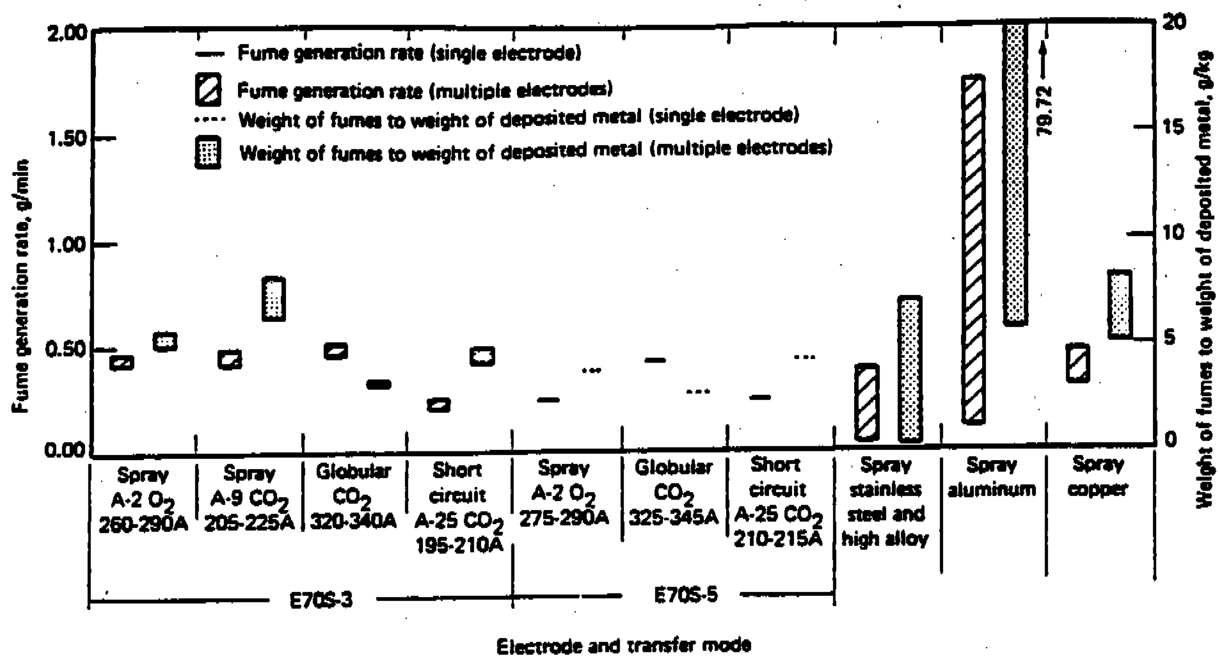

Fig. 2.8–Fume generation rates and ratios of weight of fumes to weight of deposition metal for gas metal arc electrodes

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_2O_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_2O)	1.0	(1.2)	2.0	(2.4)	4-6	(4.8-7.2)
Na	(Na_2O)	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_2O_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.

ences in the metal deposition rates for the respective electrodes. Under short circuiting conditions with Ar-25 CO_2 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 normalizing[7] 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 CO_2 shielding, followed approximately in descending order by spray transfer welding with AR-2 O_2, short cuiting transfer welding with Ar-25 CO_2, and glob transfer welding with CO_2. The effects of shielding on fume generation rates can be best observed by c paring the rates at which fumes were produced du: spray transfer welding with Ar-2 O_2 or Ar-9 CO_2 shi ing. When Ar-9 CO_2 was used, the fume generation much higher than when Ar-2 O_2 shielding was used. reflects the higher oxidation potential of the Ar-9 (shielding gas, and the fume generation rate presuma would increase further if the content of CO_2 in the arg based shielding gas was increased.

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

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

(3) High Alloy Electrodes. Five high alloy elec trodes (one stainless steel electrode, three nickel bas electrodes, and one cobalt-base electrode) were invest: gated during this program, and all but one had fum generation rates and ratios of weight of fumes to weigh of deposited metal well below those of carbon stee electrodes. This trend was also observed with covere electrodes of the same types. The exception, a nickel base electrode, had fume generation rates approachin

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 othe than 0.045 in. (1.1 mm) were used in a few instances; such de viations 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:

	Fume composition, weight percent						
Electrode no.	Fe	(Fe_2O_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

	Electrode		
Characteristic	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. of the other variables affecting fume production are

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

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

Current Effects

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

Covered Electrodes. Fume generation rate as a funct of current is shown in Fig. 2.9 for 4 mm (5/32 in.) E6 and E7018 electrodes; the data forming the basis for t figure are contained in Tables B26 and B27. In e instance, these rates varied nonlinearly with curre Studies to fit the data to a power function indicated t the fume generation rate (FGR) relation to current w different for each type of electrode. For example, 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 comparison purposes.

The results obtained are similar to those obtained other investigators. Kobayashi, Maki, and Ohe not that fume generation rates for ilmenite, lime, and lim titania covered electrodes varied with current to powe of 1.17 to 1.74 (Ref. 2.5). Agreement with their resu was good considering differences between domestic a foreign electrodes and differences in fume sampli methods. In work done by Heile and Hill with E6010 ar E7018 electrodes, similar trends in fume generation rat were observed (Ref. 2.3).

Flux Cored Electrodes. The effects of welding curre on fume generation rates for a 2.31 mm (3/32 in.) diame ter E70T-1 electrode using CO_2 shielding are also show in Fig. 2.9; details on the welding conditions and the re sults of this investigation are provided in Table B2 Above 450 A, the fume generation rate increased almo linearly with current; below 450 A, the behavior of th fume generation rate with current was nonlinear. In par ticular, there was a well-defined and reproducible mir imum at low current levels that may have been caused b

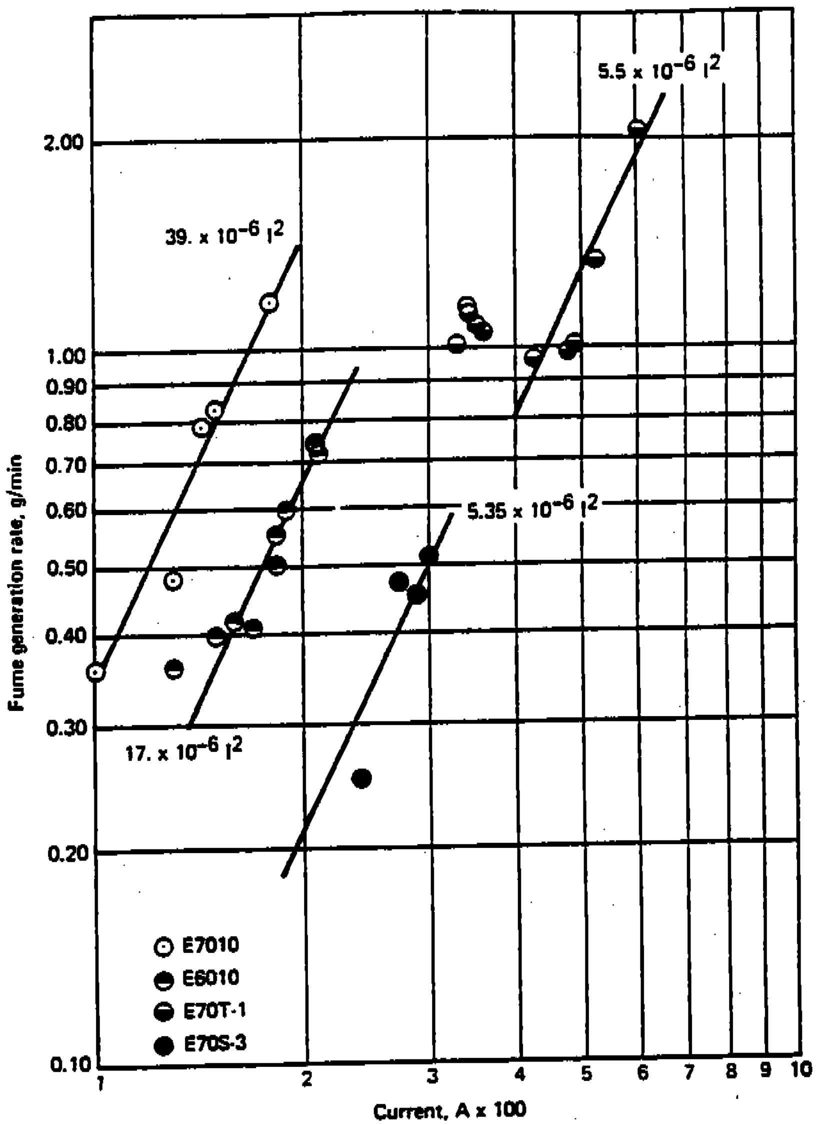

Fig. 2.9—Fume generation rates for selected covered, flux cored, and solid GMAW electrodes as a function of current

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.

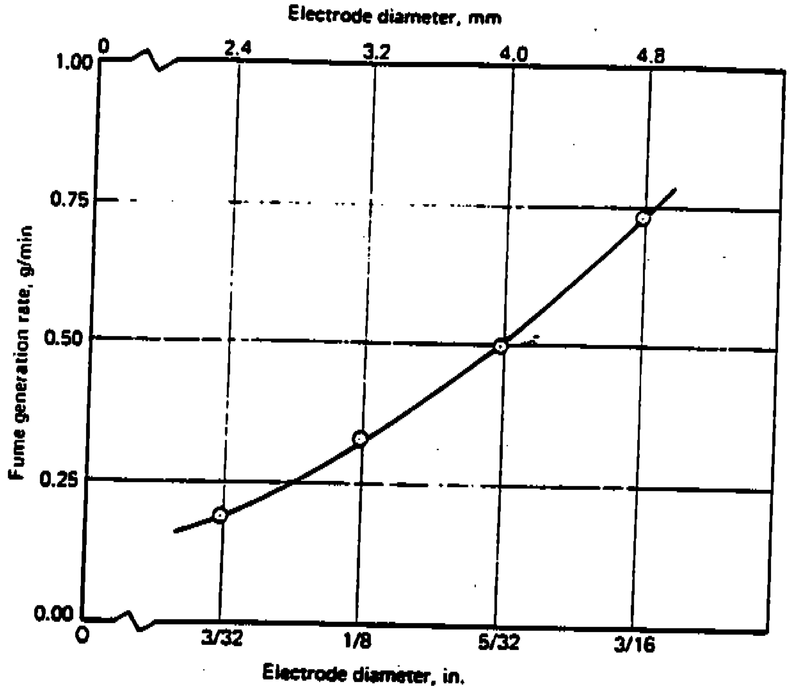

Fig. 2.11—Fume generation rates for E7018 covered electrodes with different diameters at constant current densities

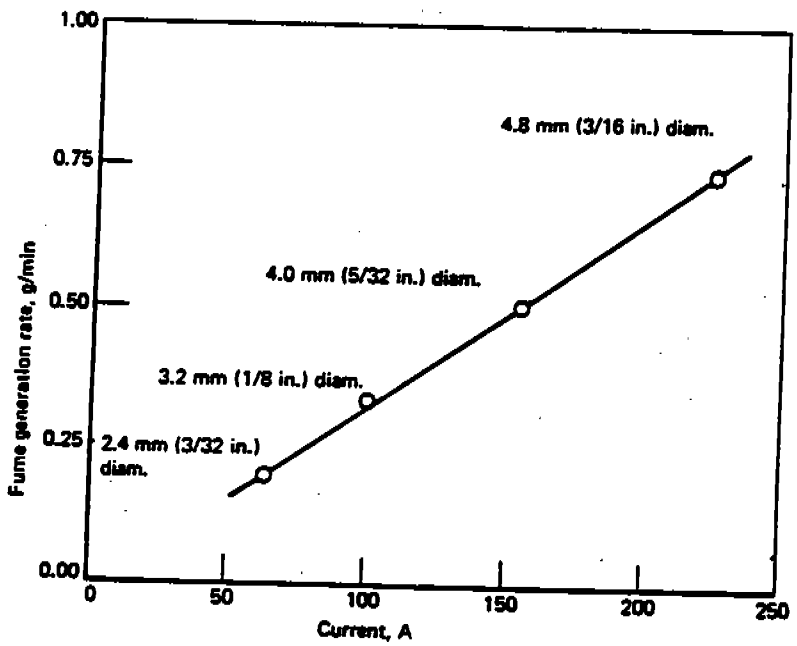

Fig. 2.12—Fume generation rates for E7018 covered electrodes with different diameters as a function of current

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 generation 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.

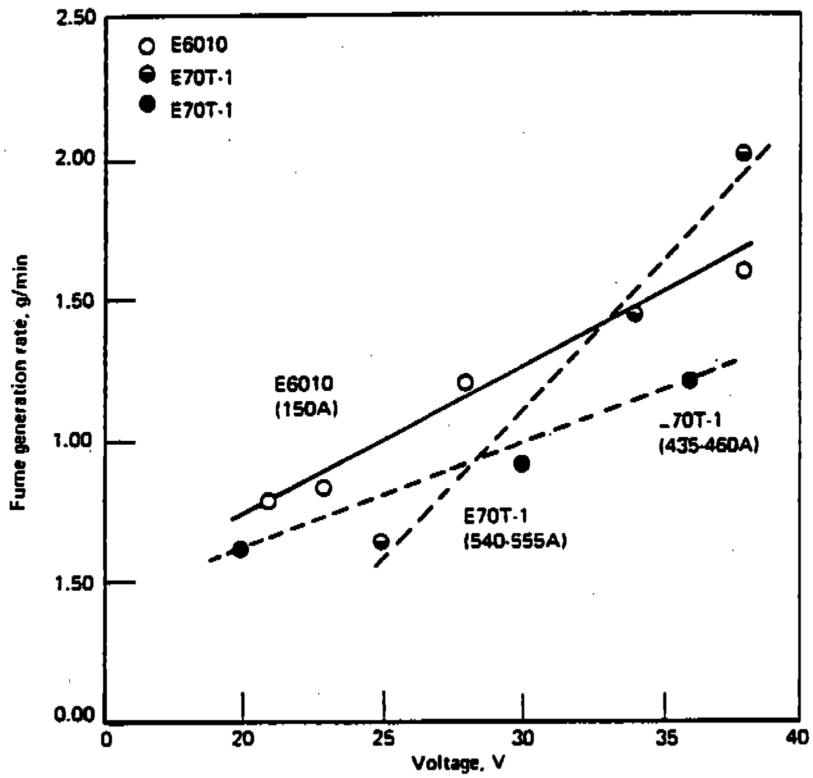

Fig. 2.13—Fume generation rates for an E6010 covered electrode and an E70T-1 flux cored electrode as a function of voltage at selected current levels

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 aver arc length over the welding interval was measured fr the plate surface to the electrode tip. It should be ε phasized that this was a subjective measurement, cause the arc length varied during welding. Since curr varied also, the fume generation rates were normalizec a current of 150 amperes to provide a common basis comparison. The results of this investigation are su marized in Fig. 2.14; supporting data are provided Table B36.

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

In a related experiment, the welding current wa

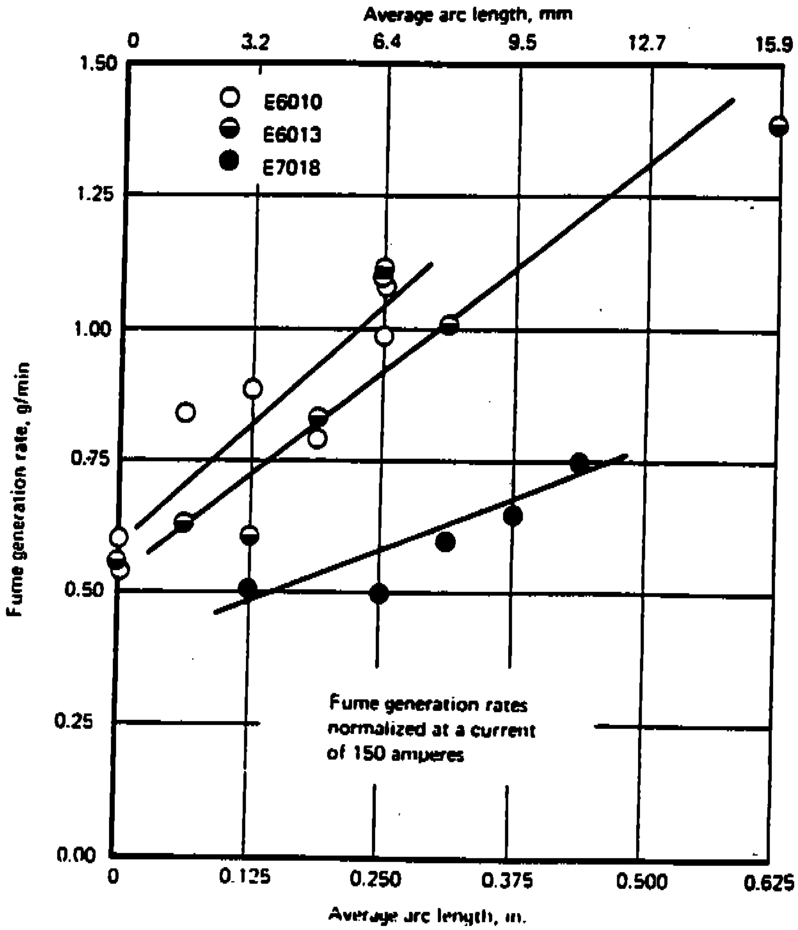

Fig. 2.14 – Fume generation rates for selected covered electrodes as a function of arc length

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.

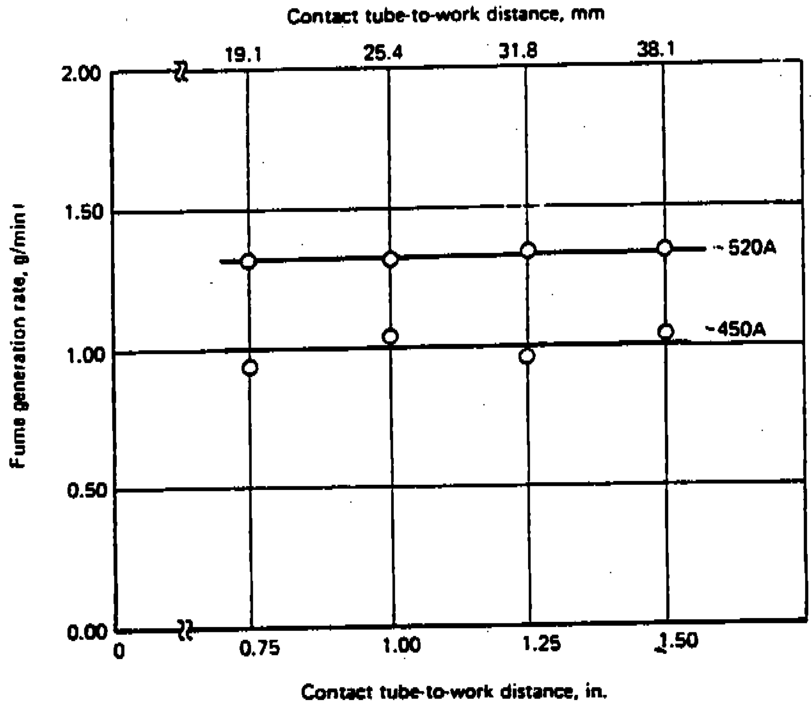

Fig. 2.15—Fume generation rate of a 2.4 mm (3/32 in.) E70T-1 flux cored electrode as a function of contact tube-to-work distance at selected constant current levels

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 CO_2 or gas mixtures containing CO_2 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 O_2 shielding, (b) spray transfer with Ar-9 CO_2 shielding, and (c) globular transfer with CO_2 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 e are shown in Table 2.14 and the apparent trend cussed below:

(1) Iron (iron oxide) contents were highe welding was done in the spray transfer mode wi Ar-2 O_2 or Ar-9 CO_2 shielding and lowest when was done in the globular transfer mode with CO_2 s These results are in agreement with those of H Hill (Ref. 2.3).

(2) Manganese (manganese oxide) conten highest when welding was done in either the spra fer mode with Ar-9 CO_2 shielding or in the globul fer mode with CO_2 shielding; this element (or ele oxide) content was lowest when welding was don spray transfer mode with Ar-2 O_2 shielding. He oxidation potential of the shielding gas had a slight on the contents of manganese (manganese oxide) fumes.

(3) Silicon (silicon dioxide) contents were h when welding was done in the globular transfer with an oxidizing gas, CO_2. These results are also in ment with those of Heile and Hill (Ref. 2.3). There w apparent explanation for the low silicon content i fumes produced by the E70S-3(54) and E70S- electrodes.

(4) Copper contents in the fumes appeared to be

Table 2.14
Effects of shielding gas on fume composition

Electrode[1]		Shielding gas	Fume sample weight, g	Composition, weight %						
				Fe	(Fe_2O_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)	0.0
E70S-3	(54)	Ar-9 CO_2	0.55	62.5	(89.4)	6.1	(9.6)	0.5	(0.8)	0.0
E70S-3	(54)	CO_2	0.42	56.3	(80.5)	6.3	(10.0)	2.3	(3.6)	0.1
E70S-3	(57)	Ar-2 O_2[2]	0.32	62.7	(89.7)	4.4	(7.0)	1.1	(1.7)	0.8
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 A-2 O_2 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 CO_2 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 A-9 CO_2 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.

-nental vaporization, condensation, .nd oxidation enhanced vaporiza- ·on.

Additional support for the vaporiza- -·· condensation-oxidation mech- (V-C-O) is also found in the data ..sented in Table 5 covering GMA ..ding of aluminum alloys. Because ..nert shielding, the mechanism for ..me generation is simply vaporiza- ..on and condensation of elemental ..aterial. Aluminum 5356 generates ..ore fume because of the additional ..ontribution of Mg. Note that the Mg ..ontent of the 5356 fume (Mg/Al = ..) is enriched over that of the wire (Mg/Al = 1/16). This results from the ..that Mg has a considerably higher ..or pressure in the range of 2000- .. K and its activity coefficient in ..ten aluminum is 0.5. In making a ..mparison of the above data, note ..at finer wires produce less fume at ..mparable currents and arc lengths.

..he above discussion applies ..ually well to fume generation in ..CA and SMA welding. In these ..ocesses, the fume results from the ..-C of elemental and lower oxide ..cies, and the V-C of oxide and ..ide flux species. As might be ex- ..ted, the composition of the fume is ..ongly dependent on flux com- ..sition since significant quantities of ..w melting point flux components are ..ntained in the fume.

.. V-C-O mechanism advanced .. .is point is essentially a simple one ..aving to do with the vapor pres- ..ures and latent heats of vaporiza- .. of the constituents present in the .. of the consumables and with the ..izing potential of the shielding .. if one is used. To first order, these ..actors determine the amount of a ..articular constituent appearing in ..he fume. Obviously, rate controlling ..teps involving diffusion of the various ..eactants and products will affect the ..FR and composition of the fume as ..ell. A more complete model re- ..ires consideration of these rate ..ntrolling factors and the dynamic ..ure of the metal transfer process ..uding such factors as residence ..e of the molten droplet at a par- ..cular temperature, degree of sur- ..ace exposed for participation in the ..aporization process, and the ef- ..ciency of energy absorption by the ..urface. These contributions will be ..onsidered in turn.

..For instance, as observed pre- ..usly, the higher FFR for CO_2 com- ..red with argon-based shield gases .. believed to be caused by the ..eater contribution of oxide species ..ing from the increased oxidizing .. .tial of the CO_2 shielding gas. Additionally, the inability to achieve ..apid drop detachment when using CO_2 may further augment the oxide enhancement. With CO_2, the molten drop of metal spends a significant fraction of the total transfer time attached to and wandering about the wire tip. This instability can produce turbulent effects resulting in contamination which, coupled with the long detachment times, can further enhance the vaporization due to oxide species over and above the natural oxidizing potential of the shield gas. The rapid drop detachment obtained in the spray mode using argon-based shield gases does not permit this condition to occur. This fact and the lower oxidizing potential of the argon-based shield gases are sufficient to account for the differences in the mean FFRs.

The problem of instabilities and turbulent effects in FCA and SMA similar to those which exist with CO_2 in GMA is compounded by the presence of extremely volatile flux components. Hence, the FFRs for these processes are substantially higher than for GMA.

In an effort to gain more precise information about how these dynamic effects affect the V-C-O process, it was felt necessary to determine where the vaporization is occurring. Two experiments were performed. The first was to examine fume formation using the GTA process. As stated earlier, no measurable amounts of fume were obtained for all currents between 50 and 450 A using argon shielding. The initial implication is that the molten metal in the weld puddle does not substantially contribute to the fume. The weld puddle is cool relative to the arc. While vaporization is occurring, the partial pressures and hence the contribution to the total fume level is substantially reduced. Adding oxygen to the shielding gas did produce small amounts of fume, supporting the hypothesis of enhanced vaporization due to oxide species.

The second experiment involved the welding of Mg bearing Al plate using the GMA process. Two wire types were employed, type 5356 containing Mg and type 1100 containing no Mg. Referring back to Table 5, Mg was found in the fume when the 5356 wires were used, but no Mg was found when the 1100 wires were used even though Mg was present in the plate in both cases. The conclusion to be drawn, therefore, is that the vaporization of elemental and oxide species is occuring at the wire tip and in the welding arc, but not in the weld puddle to any comparable degree. This is totally consistent with known temperature distributions of the arc.

A feeling for just how the fume evolution is affected by the welding conditions and shielding gas can now be gained by a more critical examination of the behavior of the fume data in CO_2 and argon-based shielding gases exhibited in Figs. 10 and 12.

The CO_2 results are presented in Fig. 12. Two features are apparent. For a given voltage, there is a monotonic increase of fume with current;

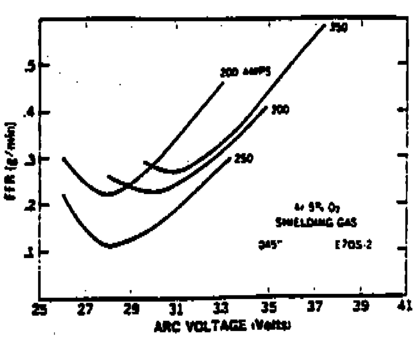

Fig. 10 — The effect of voltage and current on the FFR in GMA welding with argon-5% O_2 shielding gas

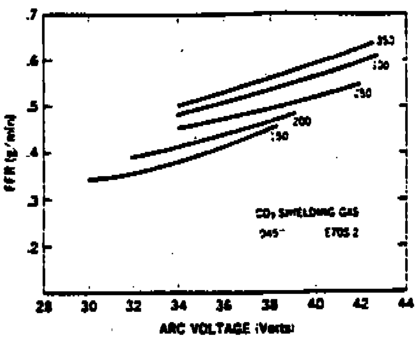

Fig. 12 — The effect of voltage and current on the FFR in GMA welding with CO_2 shielding gas

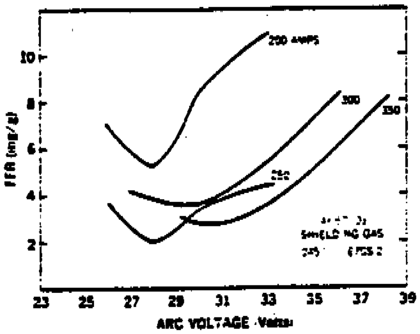

Fig. 11 — Data of Fig. 10 replotted in mg/g

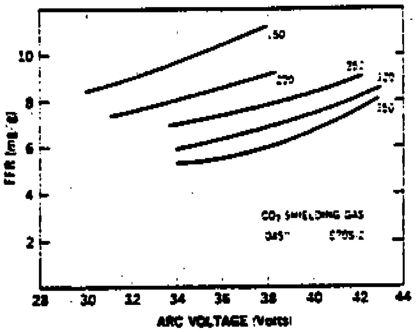

Fig. 13 — Data of Fig. 12 replotted in mg/g

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: Measured, g/min	Normalized[1], g/min	Weight of fume/ wgt. of deposited metal, g/kg[2]
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 we: deposited as well as that of the electrode. When the E31(16 electrode was evaluated on stainless steel, the fume contained higher contents of manganese, nickel, ar chromium than when this electrode was used on carbo steel (Table 2.17). The effects of the electrode itself c fume composition can be estimated by examining th composition of the fumes produced when welds we: deposited on carbon steel. The difference between th contents of manganese, nickel, and chromium in th sample and in the sample collected when welding w: done on stainless steel represents the effects of the stai less steel base plate on fume composition. It was co cluded that electrode and base plate should be matche if fume compositions are to be determined.

Diameter Effects with Flux Cored Electrodes. Th fume generation characteristics of a 1.6 mm (1/16 in diameter E70T-1 electrode were compared to those of 2.4 mm (3/32 in.) diameter electrode made by the sam manufacturer. Welding was done at current levels appro priate for the respective electrodes and CO_2 was used fo shielding (Table B41). Data on the "as measured" an "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 diam eter electrode was less than that associated with the larg diameter electrode. However, when the effect of curren on this characteristic was taken into account by normaliz ing 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 estimated 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

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 Fe	Mn	Si	Ni	Cu	Cr	Mo	Al	Mg	F	Other
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	---	---	---	---	---	---	---
ENi-Cl	28	0.35	2.5	0.3	---	6.9	<0.1	---	---	---	---	10.0[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	5.9	2.1	---	---	---	---
Haynes C-276[8]	69	0.35	0.3	0.3	---	1.1	---	2.5	0.6	1.0	1.4	5.9[1]	0.1Co-0.1W-2.4Ca-4.9Ti
Haynes 25[8]	70	0.25	---	4.6	---	1.8	---	6.9	---	1.1	0.1	7.7[1]	7.7Co-1.3W-2.4Ca-5.3Ti
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	Fe	Mn	Si	Ni	Cu	Cr	Mo	Al	Mg	F	Other
			Concentration, weight percent										
			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 O_2
5. Shielding gas: A-9 CO_2
6. Shielding gas: CO_2
7. TM, International Nickel Company

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 semiquantitative 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 electrodes[1] 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.