THE WELDING ENVIRONMENT

A Research Report on Fumes and Gases Generated During Welding Operations

Research performed at Battelle-Columbus Laboratories
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Under the direction of the AWS Technical Activities Committee's
Task Group on Welding Fume Research

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bon steel is welded with the CO_2-metal-arc process using a copper-coated solid electrode, the following contaminants will (or may) be present in significant amounts in the welding fumes and gases:

Fumes	Gases
Fe_2O_3	CO
MnO_x	CO_2
SiO_2	NO_x
Cu	O_3

In this case, optical emission spectroscopy would be used to determine the elemental concentrations of iron, manganese, silicon, and copper since all of these elements are expected to be present in significant quantities. The concentrations of carbon dioxide and nitrogen oxides would be determined by gas mass spectroscopy; another technique, such as the Saltzman method, would be used to detect the presence of nitrogen dioxide if this information were needed. Gas chromatography would be used to determine the concentration of carbon monoxide. Procedures for detecting the presence of ozone in welding fumes require more research to develop a reliable method.

It should be recognized that the spectrograph contains information on concentrations of elements other than those listed in the example. Therefore, the entire spectrograph should be examined for unsuspected elements that may be present in hygienically significant amounts.

Wet chemical methods can also be used to detect the presence of specific elements and compounds in welding fumes and gases. Such methods can be readily mastered, and they produce accurate results at low costs during routine use. If multiple wet chemical analyses must be made for several elements, the total cost may exceed that of a spectrographic analysis. Also, the use of wet chemical methods does not permit the detection of unexpected potentially hazardous elements.

It has been suggested that the hygienic hazards associated with a particular welding operation could be determined by analyzing the fumes and gases for a single element. This suggestion would be valid if the proportions of the fume constituents remained constant, regardless of the welding conditions. Such is not the case, however. For example, in work conducted by Thrysin, the amount of iron oxide produced during welding with a specific low-hydrogen electrode varied nonlinearly from about 38 to 43% as the welding current was increased from 400 to 800 A.[10] Changes in the proportions of other fume constituents varied also. Similar results were observed during other work conducted at Battelle-Columbus.

TOTAL FUME STUDIES

OBJECTIVE

The objective of this task was to select and evaluate methods to measure the total quantity of fumes produced during welding with E11018, E70S-3, E70T-1, E70T-4, and EM12K electrodes, and determine the distribution of fume particles according to size for the same welding electrodes.

Data on fume quantities and fume generation rates are important for these reasons:

(1) The fume generation rate can be used to indicate the buildup of potentially hazardous fumes associated with the use of a particular electrode.

(2) The fume generation rate can be used to predict ventilation requirements.

(3) Total fume data can be used in product development activities.

The classification of fume particles according to size is important from the hygienic standpoint because the quantity of fumes that is retained in the human respiratory system and the depth in the system to which they penetrate are largely functions of particle size. Data on fume particle sizes are also important in the selection of ventilating equipment and devices (scrubbers, precipitators, etc.) to remove or collect fumes from the atmosphere surrounding welding operations.

PROCEDURES

Total Fume Measurements

During studies to measure total fume quantities, welding was done in a partially closed chamber. An absolute filter plus prefilters were used to collect the fumes produced by E11018, E70S-3, E70T-1, and E70T-4 electrodes; prefilters were not required during the collection of fumes produced by the two submerged arc welding electrodes, EM12K.

The fume samples were collected in triplicate at each of two representative welding current levels. Triplicate samples were obtained to permit averaging of the data in order to minimize scatter attributable to minor variations in the welding or sampling procedures. The welding conditions are shown in Table 2.9.*

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*It should be noted that two tests were conducted with the EM12K electrode designated as No. 1 to determine if the method of applying the flux (that is, before or during welding) influenced the amount of fumes produced during welding. Since the flux deposition method did not significantly affect the fume generation rate, only one test was conducted with the EM12K No. 2 electrode. A higher welding current was used for this test than those conducted with the other submerged arc welding electrode to determine if the fume quantities would be increased appreciably.

TABLE 2.9. WELDING CONDITIONS FOR TOTAL FUME STUDIES

Electrode	Electrode Diameter, in.	Current, A (Nominal)	Voltage, V	Shielding Gas	Wire Feed Rate, ipm (Average)	Contact-to-Work, in.	Welding Time, s
E11018	3/16	150	20–30	N/A(1)	N/A	N/A	90–100
		200	20–35	N/A	N/A	N/A	115–118
E70S-3	0.045	250	30–31	CO_2	428	3/4	110–120
		300	29–30	CO_2	607	3/4	110–120
E70T-1	3/32	400	31–32	CO_2	142	1	30
		500	30–31	CO_2	186	1	30
E70T-4	3/32	400	31–32	None	140	1	30
		500	30–31	None	220	1	30
EM12K No. 1(2)	3/32	400	32–33	None	84	1-1/4	120
		500	31–32	None	138	1-1/4	120
EM12K No. 1(3)	3/32	400	32–33	None	92	1-1/4	120
		500	31–32	None	145	1-1/4	120
EM12K No. 2(2)	3/32	500	31–32	None	144	1-1/4	120
		600	29–31	None	193	1-1/4	120

(1) N/A: not applicable
(2) Flux poured on plate before welding
(3) Flux poured on plate during welding

The fume samples were collected in accordance with the procedures outlined earlier.

The data obtained during these studies (fume weight, weight of filler metal consumed, and sampling time) permitted calculation of the fume generation rate, and the weight of electrode converted to fumes. For comparison purposes, the fume generation rates were normalized on a per-minute basis. In calculating the weight of electrode converted to fumes, the total electrode weight (metal weight plus flux or covering weight) was used because the amount of fumes produced during welding is dependent on the flux or covering and the metallic portion of the electrode. Repeated measurements indicated that the flux in the E70T-1 and E70T-4 electrodes used in this program accounted for 14 and 15% of the electrode weight, respectively; the covering of the E11018 electrode amounted to about 30% of the electrode weight.

Fume Particle Size Classification

A cascade impactor was used to classify the fume particles according to size. The manner in which particle classification is accomplished with this equipment has been discussed previously.

The particle size distribution was determined on a weight basis in accordance with the procedures outlined earlier. To insure that sufficient fumes would be available for collection near the inlet, the cascade impactor was placed inside the welding chamber that was used for total fume measurements; the impactor inlet was located about 16 in. above and 8 in. to the side of the arc. The operating vacuum for the impactor was provided by a small pump.

Two particle size analyses of the fumes produced by each of the E11018, E70S-3, E70T-1, and E70T-4 electrodes were made with the cascade impactor; the conditions for the analyses of fumes produced by one electrode differed only in the length of the welding or sampling period or both. Only one analysis of the fumes produced by each of the EM12K electrodes was made, because the quantity of fumes evolved during submerged arc welding was insignificant, unless the arc broke through the flux cover.

The welding and sampling conditions for each particle size analysis are shown in Table 2.10.

RESULTS AND DISCUSSION

Total Fume Measurements

The results of these fume studies are summarized in Table 2.11. For easy comparison, the fume generation

TABLE 2.10. WELDING CONDITIONS FOR FUME PARTICLE SIZE ANALYSIS

Electrode	Electrode Diameter, in.	Current, A (Nominal)	Voltage, V	Shielding Gas	Wire Feed Rate, ipm	Contact-to-Work, in.	Welding Time, s	Sampl Time, s(1
E11018	3/16	150	20-30	N/A(2)	N/A	N/A	45	105
		150	20-30	N/A	N/A	N/A	45	150
E70S-3	0.045	250	30-31	CO_2	450	3/4	60	240
		250	30-31	CO_2	450	3/4	60	180
E70T-1	3/32	500	30-31	CO_2	170	1	30	90
		500	30-31	CO_2	170	1	60	180
E70T-4	3/32	500	30-31	None	216	1	60	180
		500	30-31	None	216	1	30	90
EM12K No. 1	3/32	600	29-30	None	180	1-1/4	180	180
EM12K No. 2	3/32	600	29-30	None	185	1-1/4	150	150

(1) Sampling was conducted during the welding cycle and for selected times thereafter to determine if the results were affected by the length of the sampling cycle.

(2) N/A - Not applicable.

rate and the weight of electrode converted to fumes are also plotted as bar graphs in Figs. 2.5 and 2.6. In each case, data for the submerged arc welding electrodes are shown separately, because the quantity of fumes produced by these electrodes was very small in comparison with that produced by shielded metal-arc and gas metal-arc welding electrodes.

The equipment and procedures used in this investigation produced consistent results within experimental limits. For example, at a current of 400 A, the weights of three fume samples collected during 30 s of welding with the E70T-1 electrode were 0.3997, 0.4059, and 0.3939 g. The mean fume weight was 0.3998 g and the standard deviation from this value was 0.0060 g.

Fume Generation Rate. Fumes were generated at the highest rate by the two flux cored arc-welding electrodes. The fume generation rates of the E11018 and E70S-3 electrodes were comparable. Fumes were produced at insignificant rates by the submerged arc welding electrodes, regardless of whether the flux was poured in the joint area before or during welding. However, in cases where the arc broke the cover momentarily, the fume generation rate increased sharply. For example, at a welding current of 500 A, the rate at which fumes were produced by one of the EM12K electrodes increased from 4.2 mg/min to 15. mg/min, even though the arc was unshielded for only few seconds.

An examination of the data contained in Table 2.11 indicates some ambiguities. With few exceptions (E70S-3 fumes and the fumes from one of the EM12K electrodes), fumes were produced at increased rates when the arc current level was increased. Other investigators have also noted an increase in the quantity of fumes produced as a function of increased welding current. For example, Thrysin reported that 1.5 g of fumes were produced at an arc current of 240 A; at 350 A, 2.1 g of fumes were produced.[10] During an investigation of the fumes associated with gas (CO_2) metal-arc welding, Erman, et al., observed that the fume generation rate increased from 0.35 to 0.84 g per min at welding currents of 190 and 300 A, respectively.[11] However, in other work where the fume generation rates for several electrodes were determined over a wide range of welding currents, the variation in fume generation rate appeared to be more complex than a simple dependence on welding current (Fig. 2.7). The fume generation rates of electrodes used for flux cored arc welding (E70T-1 and E70T-4) increased to a maximum with increasing arc current and then de-

TABLE 2.11. SUMMARY OF DATA O[illegible]AL FUME MEASUREMENTS

Electrode (AWS Designation)	Current, A (Nominal)	Fume Generation Rate, g/min(1)		Weight of Electrode Converted to Fumes, %		Remarks
		Average	Std. Dev.	Average	Std. Dev.	
E11018	150	0.3770	0.0103	1.110	0.052	
	200	0.4390	0.0055	1.110	0.014	Arc interrupted; average values based on two samples
E70S-3	250	0.4150	0.0273	0.475	0.011	Arc interrupted; average values based on two samples
	300	0.2570	0.0304	0.212	0.013	
E70T-1	400	0.7996	0.0120	0.776	0.012	
	500	0.8994	0.0300	0.670	0.017	
E70T-4	400	2.0310	0.0187	1.990	0.021	
	500	2.5106	0.2310	1.550	0.168	
EM12K No. 1(2)	400	0.0310	0.0016	0.0041	0.0020	Arc broke cover; average values based on two samples
	500	0.0042	0.0010	0.0034	0.0007	
EM12K No. 1(3)	400	0.0012	0.0007	0.0015	0.0011	
	500	0.0029	0.0009	0.0022	0.0007	
EM12K No. 2(2)	500	0.00166	0.0005	0.0014	0.0002	
	600	0.00029	0.00004	0.00016	0.00002	Arc broke cover; average values based on two samples

(1) Average values based on three samples

(2) Flux poured on plate before welding

(3) Flux poured on plate during welding

(4) Electrode weight is equal to sum of metal weight plus flux (or electrode covering) weight.

creased. The opposite variation in fume generation rate was observed for an electrode used for gas (CO_2) metal-arc welding.

It is believed that the rate at which fumes are generated is largely dependent on the stability of the welding arc and its metal-transfer characteristics. The fume generation rate could also be affected by process variables other than arc current such as arc voltage, electrode stick-out, shielding gas type and gas flow rate. More work on the fundamental nature of fumes and the mechanics of fume generation is needed to explain the observations made during this program.

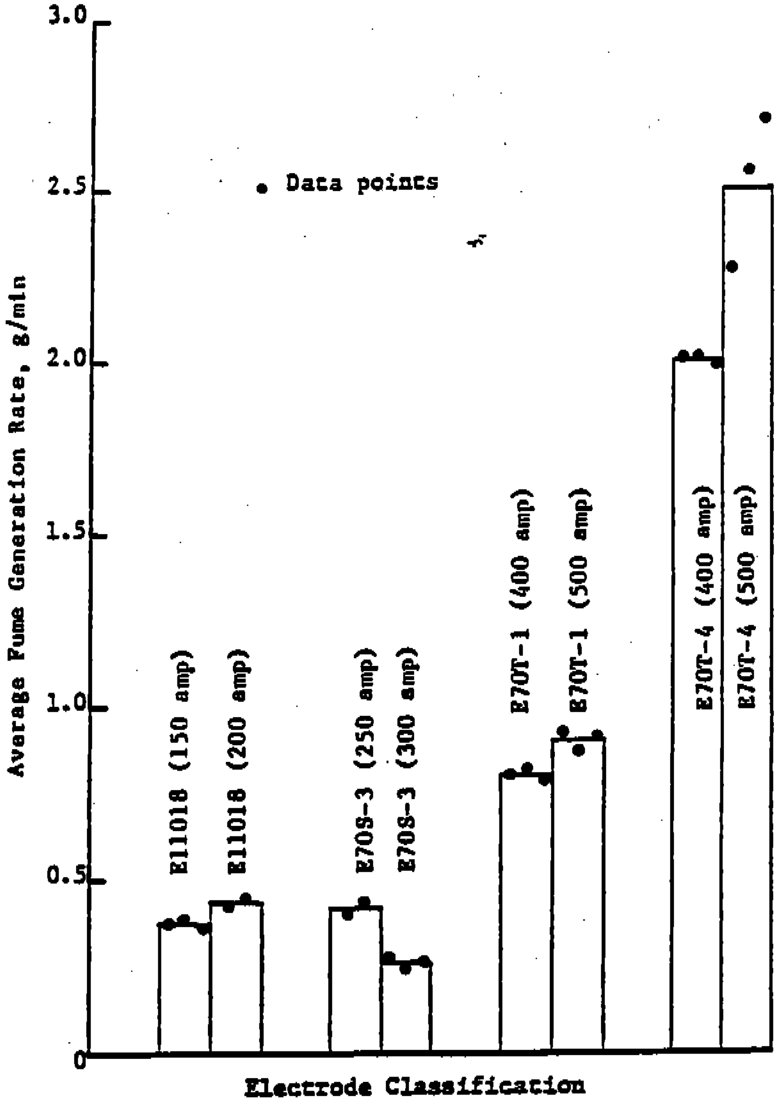
Electrode Conversion to Fumes. The E70T-4 electrode produced the most fumes per unit weight of electrode consumed, followed in decreasing order by the E11018, E70T-1, E70S-3, and EM12K electrodes.

As in the case of the fume generation rate, the effect of the welding current on the amount of the electrode that was converted to fumes is not clearly evident from the data shown in Fig. 2.6. At the current levels investigated during this program, a decrease in this parameter usually occurred when the welding current was increased. However, this relationship was not consistent when the welding current was varied over a wide range (Fig. 2.8). The amount of the E70T-4 electrode that was converted to fumes increased to a maximum and then decreased as the welding current was increased; the opposite behavior was observed for the E70S-3 electrode. The most consistent dependence of this parameter on current was noted when the E70T-1 electrode was used for welding. The amount of electrode converted to fumes is affected by the same parameters as the fume generation rate.

Fume Particle Size Classification

The results of the studies to classify fume particles according to size are shown in Tables 2.12 through 2.16. With few exceptions, the fume particles produced during welding were smaller than 1.0 μm in size. These results are in substantial agreement with those obtained by other investigators.[12, 13]

On the average, the particles in the fumes produced by the E11018 electrode were larger than those associated with the electrodes used for gas metal-arc and submerged arc welding. A sizeable proportion of the E11018 fume particles had sizes of 1.0 to 2.0 μm while the particle sizes of fumes produced with other

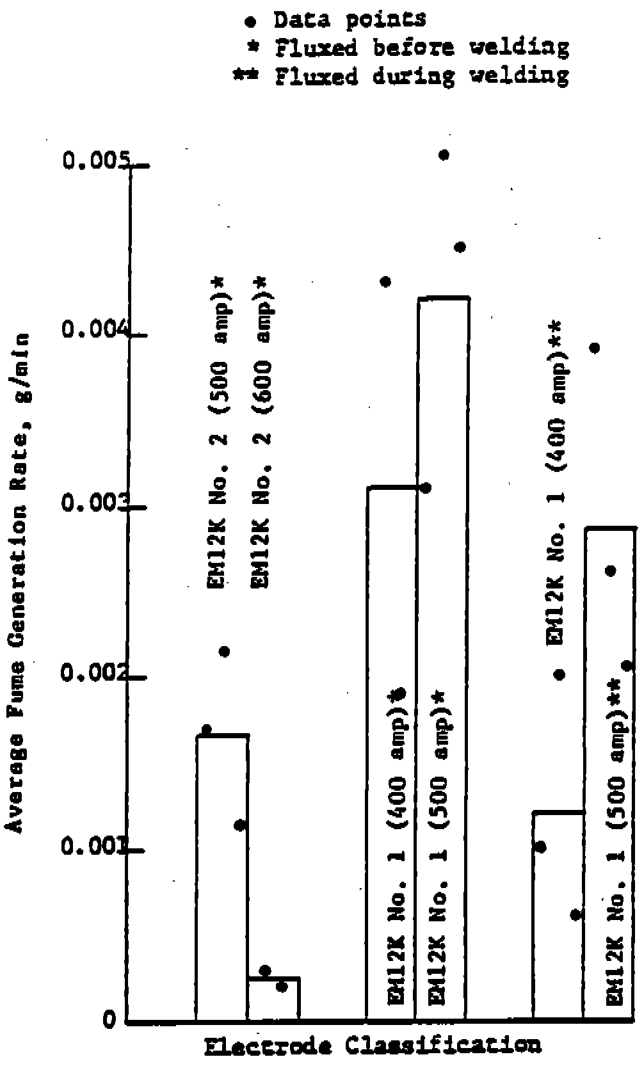


(a) Shielded metal-arc, Gas metal-arc, and Flux cored Arc Processes

Fig. 2.5—Fume generation rate as a function of electrode classification and current.

electrodes were 1.0 μm or less. It is believed that the presence of these large particles can be attributed to arc instability during shielded metal-arc welding and to the agglomeration (or coagulation) characteristics of the fumes. These same factors could also account in part for the large amount of fumes collected during the second test with the E11018 electrode. Some increase in fume weight over that collected during the first test with this electrode was expected because the sampling period was lengthened; however, the magnitude of the increase was unexpected.

A relatively short welding period had to be used in classifying the fume particles produced by the E70T-4 electrode to prevent overloading the cascade impactor. Because of the high fume generation rate associated with this electrode, wall losses (that is, some fume particles collected on the inner walls of the impactor instead of on the impactor filters) occurred at longer



(b) Submerged Arc Process

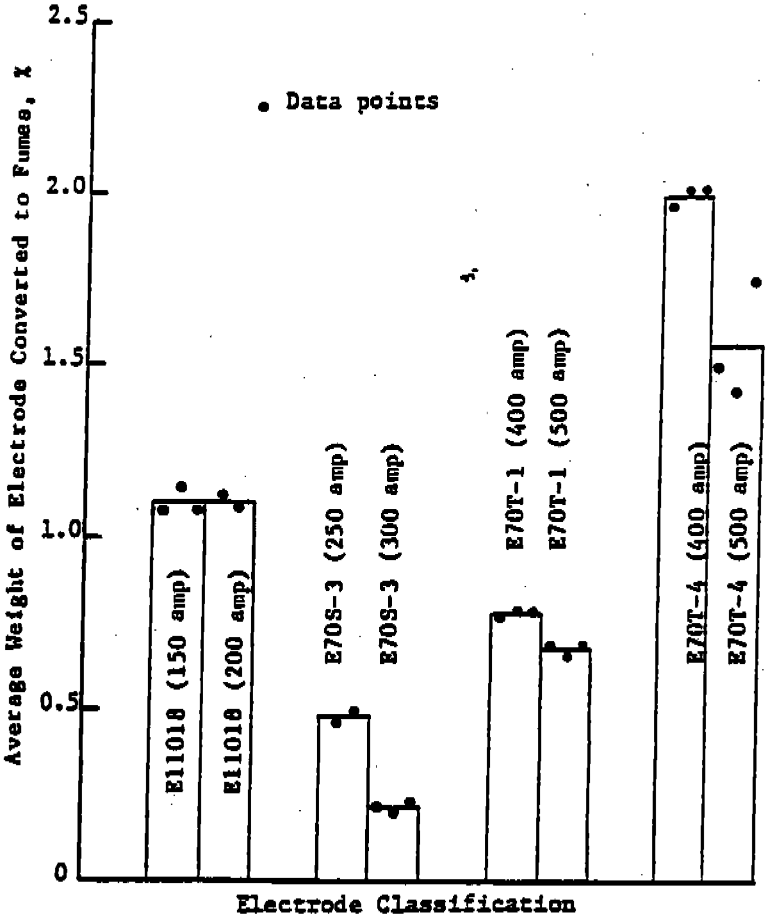
Fig. 2.5—(Continued). (Note change in vertical scale.)

welding times, and a valid classification of the fume particles was not possible.

CONCLUSIONS

The equipment and procedures used to determine the total quantities of fumes produced as a function of welding current and welding time and to classify fume particles according to size have produced reasonable results with electrodes used for shielded metal-arc, gas metal-arc, flux cored arc, and submerged arc welding. As a result, the use of such techniques or their equivalent by industry is recommended.

The importance of the fume generation rate can be judged by considering the fume concentrations that will exist in a closed area unless adequate ventilation is provided. For example, if iron oxide fumes are being generated at the rate of 1 g/min in an unventilated room with a volume of 10,000 cu ft (283.2 m^3), the total fume concentration will exceed the threshold limit value for iron oxide (10 mg/m^3) in less than 3 min, if it is assumed that the fumes diffuse uniformly throughout the room. Such is not the case, of course, since fume particles are subject to gravitational forces and the effects of air currents. For a room of this size the publication, "Safety in Welding and Cutting," (ANSI Standard Z49.1-1967) recommends that general



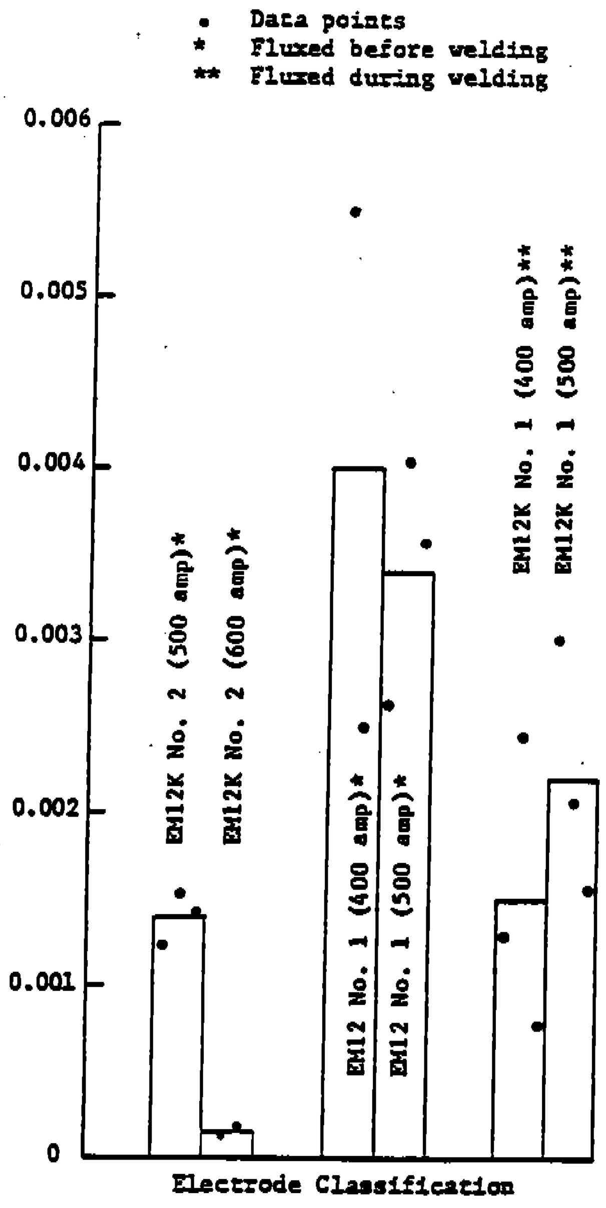
(a) Shielded Metal-Arc, Gas Metal-Arc, and Flux Cored Arc Processes

Fig. 2.6—Weight of electrode converted to fumes as a function of electrode classification and current.

ventilation at 2000 cfm be provided for each welder unless local exhaust hoods are available. This may or may not be adequate depending on the electrode being used and the rate at which fumes are being generated.

The hazards that may be associated with welding operations could be minimized if information were available on the rate at which fumes are generated by particular electrodes. It is not known if the fume generation rate is characteristic of a class of electrodes or if it is different for various electrodes of the same class. In the case of bare, solid electrodes (for example, E70S-3), it is believed that the fume generation rate and other fume characteristics should be similar for all electrodes corresponding to a single classification, regardless of the producer. Such is not expected to be the case for covered and flux cored electrodes because of differences in the compositions of the covering or flux.

With the exception of the fumes associated with the E11018 electrode, the particle sizes of fumes produced during welding were smaller than 1.0 μm in size (some particles in E11018 fumes had sizes of 1.0 to 2.0 μm). Since the sizes of welding fume particles are well within the range where maximum retention in the lower parts of the human respiratory system occurs,[14 to 18] it appears that further efforts to classify particles according to size or shape is not needed. Instead, such efforts should be directed toward minimizing the fumes in the welding area.



(b) Submerged Arc Process

Fig. 2.6—(Continued). (Note change in vertical scale.)

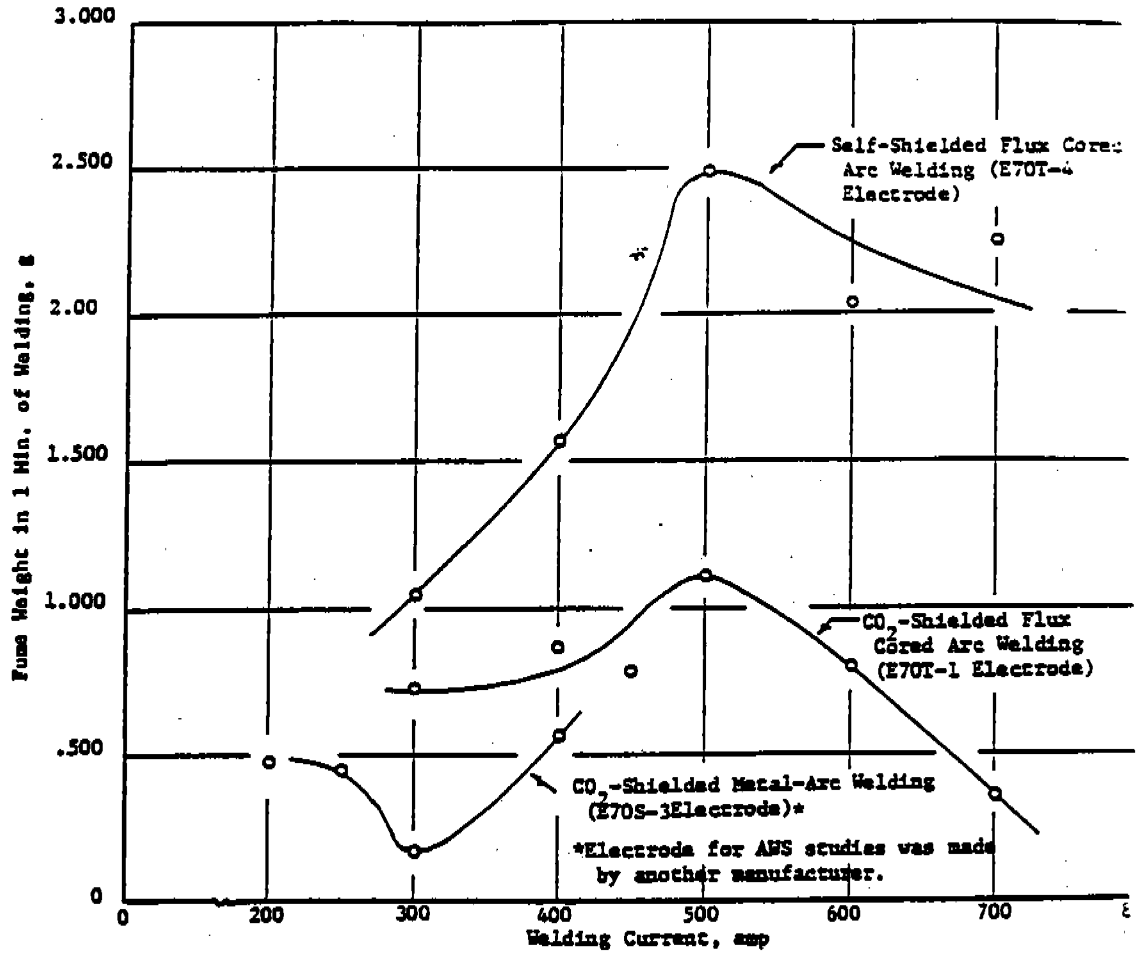


Fig. 2.7—Fume generation as a function of welding current. (Data obtained during another investigation conducted at Battelle-Columb

TABLE 2.12. CASCADE IMPACTOR PARTICLE-SIZE ANALYSIS OF E11018 WELDING FUMES

Impactor		Run No. 1(1)			Run No. 2(2)		
Stage No.	Jet Cutoff, μ	Fume Wt. mg	%	Cumulative Wt., %	Fume Wt. mg	%	Cumulative Wt., %
1	16	—	—	—	—	—	—
2	8	—	—	—	—	—	—
3	4	—	—	—	—	—	—
4	2	—	—	—	—	—	—
5	1	0.2	13.3	100.0	5.2	61.9	100.0
6	0.5	0.5	33.3	86.7	2.3	27.4	38.1
7	0.25	0.7	46.7	53.4	0.7	8.3	10.7
-	<0.25	0.1	6.7	6.7	0.2	2.4	2.4

(1) Welding current: 150 A; welding time: 45 s; sampling time: 105 s (45 s during welding +60 s after welding).

(2) Welding current: 150 A; welding time: 45 s; sampling time: 150 s (45 s during welding +105 s after welding).

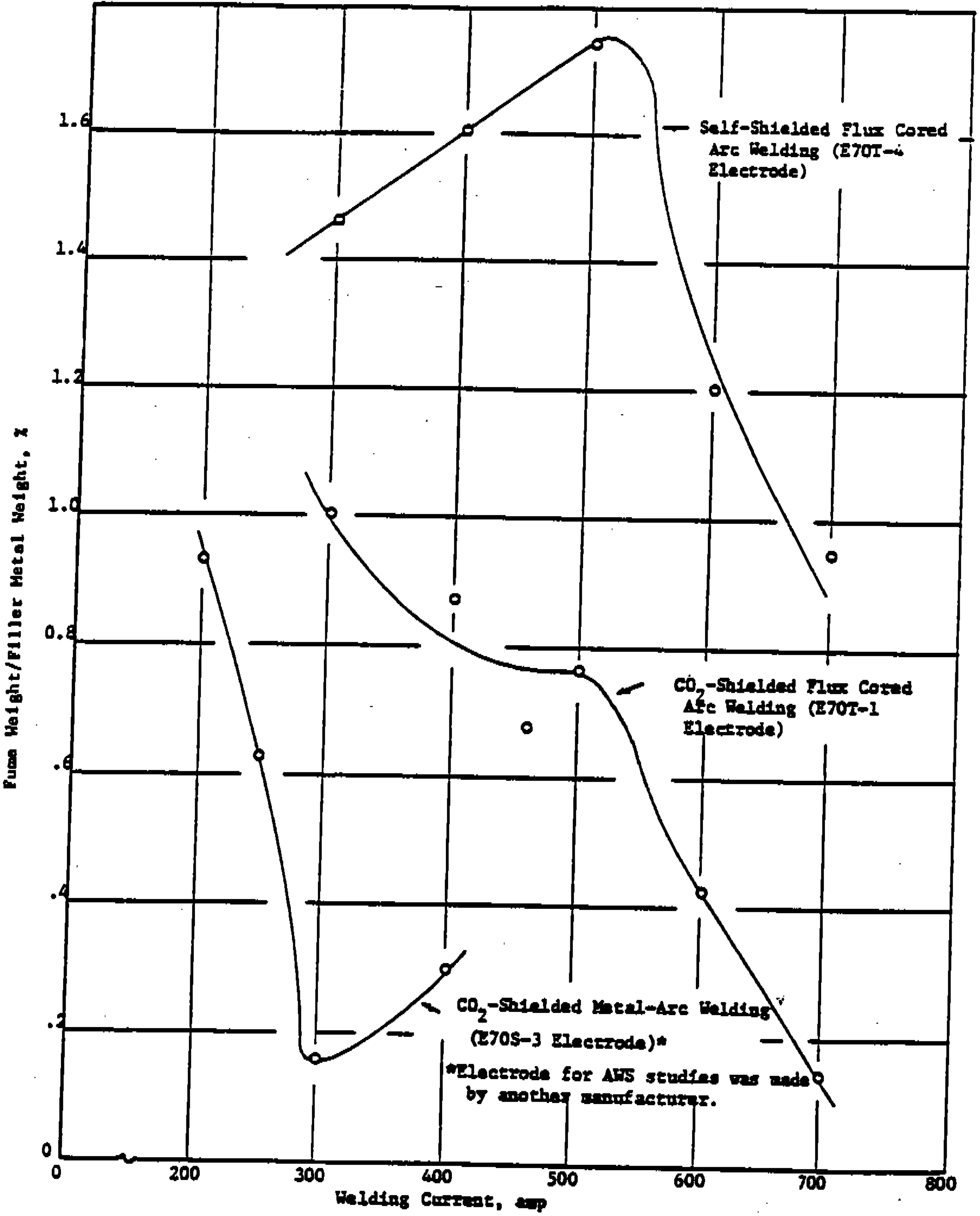


Fig. 2.8—Amount of filler metal converted to fumes vs. welding current. (Data obtained during another investigation conducted at Battelle-Columbus).

TABLE 2.13. CASCADE IMPACTOR PARTICLE-SIZE ANALYSIS OF E70S-3 WELDING FUMES

Impactor		Run No. 1(1)			Run No. 2(2)		
Stage No.	Jet Cutoff, μ	Fume mg	Wt. %	Cumulative Wt., %	Fume mg	Wt. %	Cumulative Wt., %
1	16	—	—	—	—	—	—
2	8	—	—	—	—	—	—
3	4	—	—	—	—	—	—
4	2	—	—	—	—	—	—
5	1	—	—	—	—	—	—
6	0.5	0.8	57.2	100.+	0.1	8.3	100.0
7	0.25	0.4	28.6	42.9	0.6	50.0	91.7
-	<0.25	0.2	14.3	14.3	0.5	41.7	41.7

(1) Welding current: 250 A; welding time: 60 s; sampling time: 240 s (60 s during welding +180 s after welding).

(2) Welding current: 250 A; welding time: 60 s; sampling time: 180 s (60 s during welding +120 s after welding).

TABLE 2.14. CASCADE IMPACTOR PARTICLE-SIZE ANALYSIS OF E70T-1 WELDING FUMES

Impactor		Run No. 1(1)			Run No. 2(2)		
Stage No.	Jet Cutoff, μm	Fume mg	Wt. %	Cumulative Wt., %	Fume mg	Wt. %	Cumulative Wt., %
1	16	—	—	—	—	—	—
2	8	—	—	—	—	—	—
3	4	—	—	—	—	—	—
4	2	—	—	—	—	—	—
5	1	—	—	—	—	—	—
6	0.5	0.2	25	100	0.2	22.2	99.9
7	0.25	0.4	50	75	0.4	44.4	77.7
-	<0.25	0.2	25	25	0.3	33.3	33.3

(1) Welding current: 500 A; welding time: 30 s; sampling time: 90 s (30 s during welding +60 s after welding).

(2) Welding current: 500 A; welding time: 60 s; sampling time: 180 s (60 s during welding +120 s after welding).

TABLE 2.15. CASCADE IMPACTOR PARTICLE-SIZE ANALYSIS OF E70T-4 WELDING FUMES

Impactor		Run No. 1(1)			Run No. 2(2)		
Stage No.	Jet Cutoff, μm	Fume mg	Wt. %	Cumulative Wt., %	Fume mg	Wt. %	Cumulative Wt., %
1	16				—	—	—
2	8				—	—	—
3	4				—	—	—
4	2	(impactor overloaded)			—	—	—
5	1				0.2	1.9	99.9
6	0.5				6.1	58.1	98.0
7	0.25				1.8	17.1	39.9
-	<0.25				2.4	22.8	22.8

(1) Welding current: 500 A; welding time: 60 s; sampling time: 80 s (60 s during welding +120 s after welding).

(2) Welding current: 500 A; welding time: 30 s; sampling time: 90 s (30 s during welding +60 s after welding).

TABLE 2.16. CASCADE IMPACTOR PARTICLE-SIZE ANALYSIS OF EM12K WELDING FUMES

Impactor		EM12K No. 1(1)			EM12K No. 2(2)		
Stage No.	Jet Cutoff, μm	Fume mg	Wt., %	Cumulative Wt., %	Fume mg	Wt., %	Cumulative Wt., %
1	16	--	--	--	--	--	--
2	8	--	--	--	--	--	--
3	4	--	--	--	--	--	--
4	2	--	--	--	--	--	--
5	1	--	--	--	--	--	--
6	0.5	--	--	--	--	--	--
7	0.25	Discoloration			Discoloration		
-	<0.25	0.1	100	100	0.1	100	100

(1) Welding current: 600 A; welding time: 150 s; sampling time: 150 s during welding.

(2) Welding current: 600 A; welding time: 180 s; sampling time: 180 s during welding.

FUME MEASUREMENTS IN THE HELMET REGION

OBJECTIVE

This task was undertaken to evaluate methods for determining the concentrations of fumes to which the welder is subjected during welding. Fume samples were collected outside and inside the welder's helmet while he was welding, and fume concentrations were calculated for comparison with established threshold limit values.

PROCEDURES

The fumes produced by E11018, E70S-3, and E70T-1 electrodes were collected on cellulosic membrane filters using equipment and procedures discussed earlier. Welding was done in the flat position; that is, the position in which the welder is subjected to maximum fume concentrations. The welding area was an open and unventilated room with an approximate volume of 2200 ft^3 (62.4 m^3); the fumes were exhausted from the room after each experimental test.

As mentioned earlier, equipment was incorporated in the fume sampling train to measure the volume of fume-laden air that passed through the filter (Fig. 2.3). This volume is required to calculate fume concentrations. To insure a relatively constant position for the sampling device, the filter holder was mounted in a hole that was drilled in the welder's helmet at a location immediately in front of his mouth and nose. Depending on the data required, the holder was mounted inside or outside the helmet (Fig. 2.4).

The welding conditions for these studies were identical to those used for the studies to evaluate analytical techniques (Table 2.3). The gun used for gas metal-arc welding with solid or flux cored filler wires was held manually, and efforts were made to maintain a constant arc length during welding. The same procedures were used for shielded metal-arc welding. During welding, the welder assumed a position that was comfortable for him; another welder might have used a slightly different position.

RESULTS AND DISCUSSION

Fume samples, in duplicate, were collected outside and inside the welder's helmet during the welding of steel with E11018, E70S-3, and E70T-1 electrodes.* The results of these studies are shown in Tables 2.17 through 2.20. A summary of the data collected is shown in Table 2.17 along with the total fume concentrations in front of and behind the welder's

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*Fume concentration is defined as a ratio of the weight of fumes collected on the filter to the volume of fume-laden air passing through the filter. For direct comparison with established threshold limit values, fume concentrations are expressed as mg/m^3.