Report of Investigations 9105

Fumes From Shielded Metal Arc Welding Electrodes

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TABLE 1. - Weld deposit compositions (filler metal specifications) for welding electrodes (13), weight percent

AWS code and electrode type	Co	Cr	Fe	Mn	Ni	Other[1]
A5.4:						
E308-16.......	NS..	18-21	Bal	0.5-2.5	9 -11	2.0
E310-16.......	NS..	25-28	Bal	1 -2.5	20 -22.5	2.0
A5.13:						
ECoCr-A.......	Bal.	25-32	Bal	2	3	10.9
A5.15:						
ENiCI.........	NS..	NS	5	1	85[2]	9.5
14 Mn-4 Cr[3].....	NS..	4- 5	8	.5-4.0	14 -16	.5
A5.1:						
E7018.........	NS..	.20	Bal	1.60	.30	1.1
A5.5:						
E11018-M......	NS..	.40	Bal	1.3-1.8	1.25- 2.50	1.3

Bal Balance. NS Not specified.
[1] Maximum.
[2] Minimum.
[3] Not classified by AWS; data supplied by manufacturers of electrodes used in this study.

hardfacing and rebuilding, welding is done in multiple layers of the weld filler metal. The weld alloy, rather than the original steel of the welded part, then becomes the substrate. To assess the effect of this new substrate on fume generation, a double-layer bead pad of the weld alloy was deposited onto a mild steel plate. After sandblast cleaning, this pad served as the new substrate for fume generation tests of that same alloy, performed in the same manner as with the mild steel plate substrates. One brand from each of the five high-alloy SMAW groups was tested this way.

RESULTS

MILD STEEL SUBSTRATE

The data collected from the tests are the weight of the fume collected, the weight of the electrode consumed, the arc time, and the chemical analysis of the fume. Welding conditions such as voltage, current, plate speed, and electrode feed rate were recorded or derived for each test. For the alloy groups, two additional quantities, a maximum allowable fume exposure and an exposure rating, have been derived from the data.

Two quantities based on the weight of fume generated are the fume generation rate, FGR, and the fume weight per weight of electrode consumed, f_e. The FGR measures the fume generating tendencies of an electrode and is used to derive the exposure rating. Where the arc is operating intermittently, as during a work shift, f_e may be more useful in estimating the amount of fume generated. In either case, the data apply to the operating conditions stated and, for the FGR at least, to the size of the electrode given.

Fume generation data for the electrode groups are listed in table 2. Each electrode brand has been given a code letter or letters. Replicates were measured on one of the brands, code D, to get an estimate of the repeatability of the experiments and analyses. Code D was chosen at random from among the electrodes in this group. Comparisons of the derived FGR and f_e values between the replicates and the original data set, using the Student t statistic (14) at the 90-pct confidence level, show no significant differences. The coefficients of variation (CV) of the data sets of code D, for both FGR and f_e

TABLE 2. - Fume generation data for electrodes

Code	Runs	Average Voltage, V	Average Current, A	FGR, mg/min	SD, mg/min	f_e, pct	SD, pct
TYPE E308-16--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
A..................	5	23	171	394	51	0.88	0.10
B..................	4	24	175	478	13	1.21	.18
C..................	5	24	173	514	27	1.31	.04
D..................	5	22	173	422	58	1.06	.14
	5	23	176	396	30	.95	.07
	6	23	174	415	27	1.04	.07
E..................	5	23	173	472	31	1.22	.07
Mean..............	NAp	23	174	440	55	1.09	.16
TYPE E310-16--dc, ELECTRODE POSITIVE; 4.76-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
F..................	3	24	163	446	26	1.11	0.06
G..................	6	23	166	540	37	1.47	.11
H[1].................	6	24	164	659	31	2.17	.13
I..................	6	23	165	455	33	1.20	.13
J..................	5	25	160	527	32	1.39	.10
Mean..............	NAp	24	164	534	84	1.51	.40
TYPE ECoCr-A--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 45-s ARC TIME							
K..................	5	26	140	766	59	2.58	0.20
L..................	5	26	137	571	77	1.77	.32
M..................	6	25	134	713	23	2.31	.07
N..................	6	24	139	1,086	74	4.29	.32
O[2].................	5	28	176	1,041	46	2.86	.11
Mean[3].............	NAp	25	138	795	204	2.79	1.01
TYPE ENiCI--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
P..................	6	24	135	612	12	2.08	0.06
Q..................	6	22	140	538	13	1.90	.08
R..................	4	24	143	598	12	1.78	.06
S..................	6	24	138	560	18	2.14	.11
T..................	5	23	139	461	16	1.38	.06
Mean..............	NAp	23	139	554	54	1.88	.28
14 Mn-4 Cr SURFACING ALLOY--dc, ELECTRODE POSITIVE; 4.76-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 20-s ARC TIME							
U..................	4	24	200	3,010	140	8.08	0.37
V..................	3	24	199	3,280	82	9.16	.10
W..................	5	24	198	3,170	270	7.81	.43
X..................	5	24	197	3,280	200	8.82	.50
Y..................	6	24	196	2,380	250	7.13	.55
Mean..............	NAp	24	198	2,980	420	8.16	.79

See explanatory notes at end of table.

TABLE 2. - Fume generation data for electrodes--Continued

Code	Runs	Average Voltage, V	Average Current, A	FGR, mg/min	SD, mg/min	f_e, pct	SD, pct
TYPE E7018--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
CC	6	24	161	459	30	1.55	0.10
DD	5	24	159	515	20	1.81	.08
EE	6	24	165	653	40	2.17	.15
FF	6	24	158	475	21	1.62	.07
GG	6	24	164	511	21	1.70	.08
Mean	NAp	24	161	523	75	1.77	.24
TYPE E11018-M--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
HH	6	24	163	445	16	1.46	0.06
II	6	24	160	561	12	1.96	.05
JJ	6	24	160	518	15	1.72	.06
KK	6	24	163	560	20	1.90	.06
LL	6	24	158	513	34	1.70	.10
Mean	NAp	24	161	520	47	1.75	.19
Mn-Cr SURFACING ALLOY FLUX-CORED WIRE--dc, ELECTRODE POSITIVE; 2.78-mm DIAM, 38-mm WIRE STICKOUT; 430-mm/min TRAVEL SPEED; 2,200-mm/min WIRE FEED; 1-min ARC TIME; NO SHIELD GAS							
Z[4]	6	30	288	5,070	200	6.2	0.24
BB[4]	5	29	317	4,320	190	5.2	.23
Mean	NAp	30	303	4,700	530	5.7	.73
AA[5]	6	30	287	5,410	620	6.1	.70

f_e Fume weight per weight of electrode consumed.
FGR Fume generation rate.
NAp Not applicable.
SD Standard deviation.

[1]Composite core.
[2]4.76-mm core diameter.
[3]Excludes code O data.
[4]Nominally 15 pct Mn, 4 pct Cr.
[5]Nominally 1.5 pct Mn, 16 pct Cr.

determinations, vary from 6.5 to 13.7 pct. These are similar to values computed for the other brands in this group.

For the most part, the results presented in the tables are straightforward. Code H electrodes, in the type E310-16 series, give higher fume generation data than do others in the group. This may be due to their unique construction. Unlike the solid filler core of the other electrodes, code H electrodes consist of a hollow tube filled with granular metal. This construction results in a larger surface area per unit weight of filler metal, thus generating more fume. Because the code O electrodes are of a larger diameter than are the other type ECoCr-A electrodes, they were tested at commensurately higher voltage and current settings, and their data were not included in calculating the means for the group. However, its FGR value, if reduced by the ratio of the group electrode cross section to its own cross section, is not significantly different from the group mean. Note also that its fume fraction, f_e, which effectively corrects for the difference in size, is quite close to that of the group mean.

TABLE 3. - Chemical composition of fumes generated from electrodes, weight percent--Continued

Code	Al	Ba	Ca	Co	[1]Cr	[2]Cr^{5+}	F	Fe	K	Mn	Na	Ni	Si	Sr	Ti
14 Mn-4 Cr SURFACING ALLOY															
U					1.9		NA	35.4		24.4	2.0	3.1	0.6		
V					1.6		NA	33.1		36.0	1.0	.3	1.8		
W					1.3		NA	36.8		26.6	1.7	2.9	2.3		
X					1.7		0	37.9		25.5	.8	2.7	.6		
Y					2.1		1.1	30.2		29.4	1.1	1.3	2.2		
Mean					1.7		.6	34.7		28.4	1.3	2.1	1.5		
SD					.30		.78	3.1		4.6	.50	1.2	.83		
TYPE E7018															
CC	0.7		10.8				1.2	29.1	14.6	8.6	3.1		5.1	NA	
DD	.6		11.0				.9	37.0	12.3	9.5	2.9		6.0	NA	
EE	1.1		11.3				0	25.3	5.0	3.9	2.7		1.3	NA	
FF	.4		10.8				9.3	24.3	11.1	5.5	1.9		4.9	NA	
GG	.2		11.4				5.8	31.9	6.7	4.5	3.9		6.3	1.0	
Mean	.6		11.1				3.4	29.5	9.9	6.4	2.9		4.7	1.0	
SD	.36		.28				4.0	5.2	4.0	2.5	.72		2.0	NAp	
TYPE E11018-M															
HH			13.0				4.7	24.5	6.8	14.5	4.4		2.0	1.2	
II			6.3				2.0	33.1	6.6	6.5	3.4		6.1	0	
JJ			10.6				8.1	33.0	.7	6.0	4.9		.4	0	
KK			10.1				5.6	36.6	3.5	6.1	5.0		2.7	0	
LL			12.9				.9	26.1	7.3	6.6	4.1		1.5	1.1	
Mean			10.6				4.3	30.7	4.4	7.9	4.4		2.5	.5	
SD			2.7				2.9	5.1	2.9	3.7	.65		2.2	.63	
Mn-Cr SURFACING ALLOY FLUX-CORED WIRE															
Z					1.7		1.7	43.4		22.3		2.0			
BB					1.7		2.4	43.9		26.6		.4			
Mean					1.7		2.0	43.7		24.5		1.2			
AA					10.5		.1	54.8		3.1		.3			

NA Not analyzed.
NAp Not applicable.
SD Standard deviation.

[1]Determined by acid leach-titration.
[2]Determined by INCO method.
[3]Single analysis run on separate sample.

NOTE.--No entry in a column indicates that element was not a fume constituent.

elements, the exposure value was calculated as

$$C_{i,max} = [\Sigma(f_{i,fume}/TLV_i)]^{-1}. \quad (3)$$

The resulting relative exposure indices for the electrode brands are given as C_m values in table 5.

A second index, the exposure rating, R, is derived from C_m and the FGR, as

$$R(m^3/min) = \frac{FGR}{C_m}. \quad (4)$$

If taken literally, it represents the amount of fresh air per minute needed to dilute the fume being generated to a safe level. It is essentially equivalent to the nominal hygienic air requirements (NHL) developed in Sweden to rate the fume hazards of electrodes numerically (14-15). The NHL, however, combines all of the components, using equation 3, thereby leading to higher values of the ratings. Also, lower TLV's, such as for Cr or Ni, are used. The NHL is given in cubic meters per hour. Because of these differences, the exposure rating R is used in this report. Values for the electrode brands appear in table 5. According to this ranking, the ECoCr-A

TABLE 4. - Threshold limit values (TLV's) for fume constituents (4), milligrams per cubic meter

	TLV		TLV		TLV
Al....	10	Cr^{6+}..	0.05	Na....	(2)
Ba....	.5	F.....	2.5	Ni....	1
Ca....	[1]1.4	Fe....	5	Si....	[3]2.8
Co....	.1	K.....	(2)	Sr....	(2)
Cr....	.5	Mn....	1	Ti....	(4)

[1]Based on 2-mg/m^3 TLV for CaO.
[2]None established in reference.
[3]Based on 6-mg/m^3 TLV for amorphous SiO_2.
[4]TLV for TiO_2 deleted from reference.

TABLE 5. - Exposure index (C_m) and exposure rating (R) values for welding electrodes

Group and code	C_m, mg/m^3	R, m^3/min	Group and code	C_m, mg/m^3	R, m^3/min	Group and code	C_m, mg/m^3	R, m^3/min
E308-16:			ECoCr-A—Con:			Mn-Cr buildup wires—Con:		
A..........	1.1	370	Mean[1]....	0.40	1,980			
B..........	1.2	400	2 SD........	±.10	±1,420	BB[2].........	3.8	1,150
C..........	.89	580	ENiCI:			Mean.....	4.1	1,140
D..........	.92	440	P..........	1.8	340	2 SD........	±1.0	±30
E..........	.94	500	Q..........	1.6	340	AA[3].........	4.8	1,140
Mean.....	1.0	460	R..........	1.7	350	E7018:		
2 SD........	±.27	±170	S..........	1.5	370	CC..........	11.6	40
E310-16:			T..........	1.2	390	DD..........	10.5	49
F..........	1.1	410	Mean.....	1.6	360	EE..........	19.8	33
G..........	1.0	520	2 SD........	±.26	±43	FF..........	18.2	26
H..........	1.1	590	Mn-Cr buildup:			GG..........	15.7	32
I..........	.92	500	U..........	4.1	730	Mean.....	15.2	36
J..........	.84	630	V..........	2.8	1,180	2 SD........	±8.1	±18
Mean.....	1.0	530	W..........	3.8	840	E11018-M:		
2 SD........	±.23	±170	X..........	3.9	840	HH..........	6.9	64
ECoCr-A:			Y..........	3.4	700	II..........	15.1	37
K..........	.36	2,150	Mean.....	3.6	860	JJ..........	13.6	38
L..........	.43	1,320	2 SD........	±1.0	±380	KK..........	13.7	41
M..........	.46	1,540	Mn-Cr buildup wires:			LL..........	11.1	46
N..........	.37	2,910				Mean.....	12.1	45
O..........	.44	2,380	Z[2]..........	4.5	1,130	2 SD........	±6.5	±22

2 SD 2 standard deviations.
[1]Excludes code O data. [2]Nominally 15 pct Mn, 4 pct Cr.
[3]Nominally 1.5 pct Mn, 16 pct Cr.

electrodes, as a group, are 55 times more hazardous to use than the carbon steel E7018 electrodes. Included in the data are two standard deviation (2 SD) values calculated from the data listed. Although not strictly justifiable from the small number of samples used, this statistic should encompass most of the electrode brands not tested.

The data in figures 2 through 5 were tested to determine fits to curves of the form $f_f = a_o + a_1 f_e$ and $f_f = a_o + a_1 f_e^{1/2} + a_2 f_e$, where f_f and f_e are the elemental fractions in the fume and electrode, respectively. Although the second curve gave slightly better fits for each of the elements, negative values for the coefficient a_1 for Cr and Fe argued in favor of linear fits for these data. Figure 2 plots data for five of the electrode groups in which Cr was a contributor to the fume. The least-squares fit shown is

$$f_{Cr,\ fume} = -0.31 + 0.66\ f_{Cr,\ elec},\qquad (5)$$

with deviations of about 24 pct. All fume fractions in equations 5 through 10 are in weight percent. More precise fits result from separately grouping the ECoCr-A or the stainless steel electrodes with Mn-Cr electrodes, giving for the ECoCr-A group

$$f_{Cr,\ fume} = -0.11 + 0.75\ f_{Cr,\ elec},\qquad (6)$$

and for the stainless steel E308-16 and E310-16 electrodes combined

$$f_{Cr,\ fume} = -0.054 + 0.57\ f_{Cr,\ elec}.\qquad (7)$$

Shown also in the figure are mean values of the weld-metal specifications for Cr in these alloy groups. These values, representing the Cr level in the weld deposit, are the only Cr fractions generally available.

Levels of hexavalent Cr in the fumes did not follow a pattern with respect to total Cr content in the electrode. The valence of the Cr is sensitive to the flux composition, which is quite complex for these electrodes.

A linear fit to the Fe data (fig. 3) is given by

$$f_{Fe,\ fume} = 0.916 + 0.45\ f_{Fe,\ elec}.\qquad (8)$$

Again, scatter is significant at about 30 pct. The weld-metal specification values are shown also. The Mn and Ni data are described by the relations

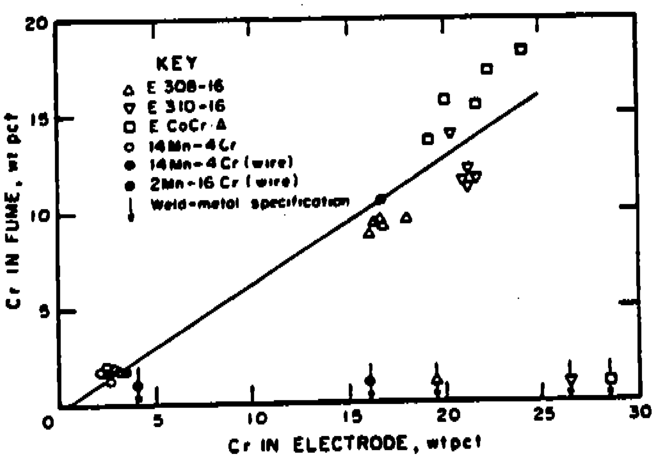

FIGURE 2.—Chromium fraction in fume as function of Cr content of electrode, including flux coating. Welding onto mild-steel plate.

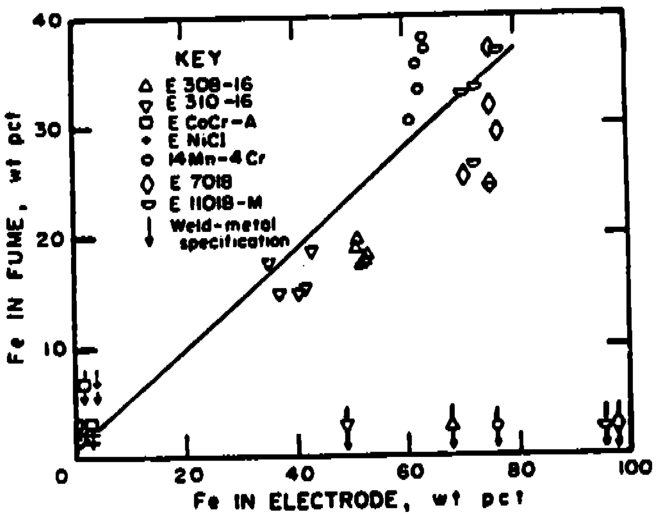

FIGURE 3.—Iron fraction in fume as function of Fe content of electrode, including flux coating. Welding onto mild-steel plate.

$$f_{Mn,fume} = -0.99 + 4.60\, f^{1/2}_{Mn,elec} + 0.57\, f_{Mn,elec}, \quad (9)$$

and

$$f_{Ni,fume} = -0.78 + 1.59\, f^{1/2}_{Ni,elec} - 0.04\, f_{Ni,elec}, \quad (10)$$

respectively. Figures 4 and 5 give the data and the weld-metal specification values. Mn comes the closest to matching these values in terms of the total electrode content. Its propensity to fume is substantially greater than that of the other metals shown, while Ni displays the least. The curves, combined in figure 6, show that these metals fume in ascending order as Ni, Fe, Cr, and Mn, roughly in proportion to their vapor pressures.

Because Co was not present in the other electrodes, the data for it were not plotted. The mean ratio of fume to electrode fractions for the five ECoCr-A electrodes is 0.54±0.06. If its fuming rate were linear with electrode content, Co would fall between Fe and Cr in fuming propensity. It does not follow in order of its vapor pressure, which is lower than that of Ni.

Partly because of the low fuming potential of Ni, the exposure index for the ENiCI electrodes was determined primarily by the Ba content of the fume, with secondary contributions from Sr and Ca. Although the fuming potentials for these elements, as determined by ratios of fume to electrode fractions, were

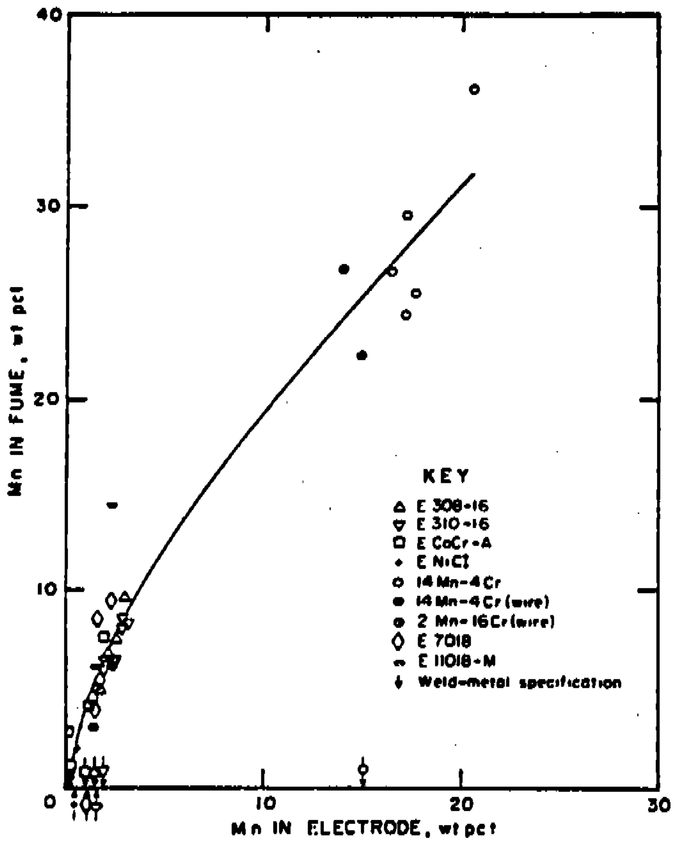

FIGURE 4.—Manganese fraction in fume as function of Mn content of electrode, including flux coating. Welding onto mild-steel plate.

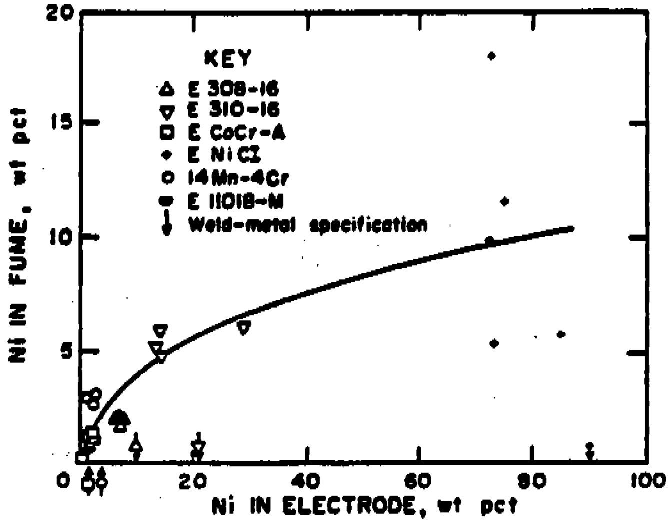

FIGURE 5.—Nickel fraction in fume as function of Ni content of electrode, including flux coating. Welding onto mild-steel plate.

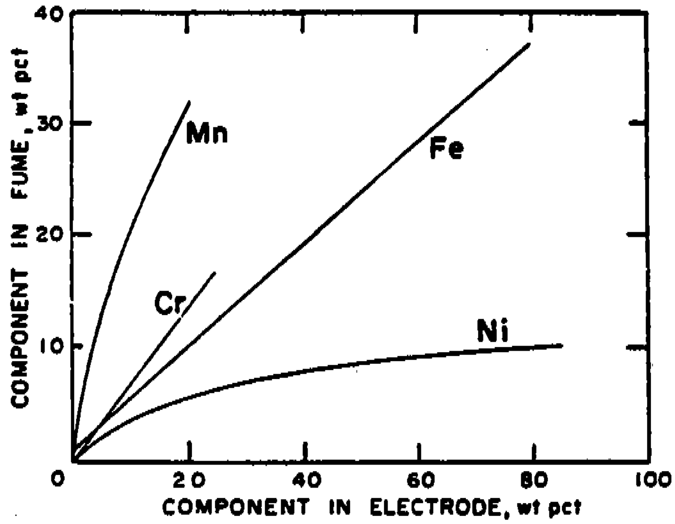

FIGURE 6.—Comparison of elemental components of fume to their respective contents in electrode.

substantially higher than for the filler metal components, the scatter was too great to be of use in predicting fume contents of untested electrodes.

ALLOY SUBSTRATE

The components of interest in the fumes of electrodes deposited onto double-layer alloy deposits (the substrate) are those found in the deposited filler metal. Fume compositions for the five electrodes tested this way appear in table 6. Except for hexavalent Cr, elements not exceeding 1 pct in the fume from mild steel welding were not analyzed for in the alloy welding fumes. Below each element fraction in the table is the ratio of it to the corresponding mild steel weld component from the fume of the same electrode code. The uncertainties are calculated from the code D replicate data (table 3) using the t statistic. Values for hexavalent Cr and Co were estimated at ±9.5 and ±6.3 wt pct, respectively. In only a few cases do the results indicate a significant increase in the component fraction arising from the alloy substrate. The 9-pct rise in Co and a 16-pct rise in Cr in the code L electrode fume are troublesome in terms of welder exposure because of their already high level in the fume. The other elements showing large fractional increases are at low enough levels as to cause minimal concern.

TABLE 6. - Chemical composition of fumes generated from electrodes weld-deposited onto double-layer alloy substrates, weight percent

	E		I		L		S		Y	
	Fume	Ratio[1]	Fume	Ratio[1]	Fume	Ratio[1]	Fume	Ratio[1]	Fume	Ratio[1]
Co......	NA	NA	NA	NA	25.4	1.09±0.07	NA	NA	NA	NA
[2]Cr.....	8.7	1.0 ±0.1	12.5	1.08±0.1	18.2	1.16± .11	NA	NA	2.1	1.0 ±0.1
Cr^{6+}....	4.2	.88± .08	4.8	.87± .08	2.0	.87± .08	NA	NA	.36	1.4 ± .1
Fe......	17.6	.94± .05	16.2	1.06± .06	2.2	.67± .04	2.7	0.93±0.05	30.8	1.02± .06
Mn......	7.2	.96± .05	7.8	.94± .05	.12	.04± .00	NA	NA	29.2	.99± .05
Ni......	2.8	1.4 ± .1	5.6	1.1 ± .1	1.1	.92± .07	10.4	.90± .07	2.5	1.9 ± .1
Si......	4.2	.95± .06	3.8	.84± .06	NA	NA	1.7	.63± .04	3.5	1.6 ± .1

NA Not analyzed.
[1]Alloy-generated component to mild-steel-generated component.
[2]Determined by acid leach-titration.

DISCUSSION

The exposure indices determined for the electrodes can be useful in a number of ways. The mining personnel responsible for specification of welding consumables could use these data to guide their selection of electrodes. Often, more highly alloyed austenitic stainless steel fillers are used to repair quenched-and-tempered steel structural components because they are considered more "forgiving" to less than optimum welding practices (16). The order of magnitude difference in exposure indices between the stainless steels and the E7018 or E11018-M steels should bias the selection towards the leaner electrodes. (It might be noted that a t statistic test shows no significant differences between the indices of E308-16 and E310-16 or between E7018 and E11018-M. A larger sampling might confirm the slight differences seen in the table.)

Knowledge of relative exposure hazards of the various types of electrodes would also alert the welder to take extra precautions during welding when using electrodes with higher exposure indices. Those with knowledge of any total fume