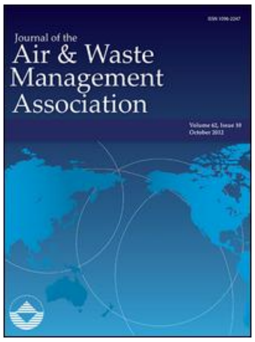

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Development of Welding Emission Factors for Cr and Cr(VI) with a Confidence Level

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ABSTRACT

Knowledge of the emission rate and release characteristics is necessary for estimating pollutant fate and transport. Because emission measurements at a facility's fence line are generally not readily available, environmental agencies in many countries are using emission factors (EFs) to indicate the quantity of certain pollutants released into the atmosphere from operations such as welding. The amount of fumes and metals generated from a welding process is dependent on many parameters, such as electrode composition, voltage, and current. Because test reports on fume generation provide different levels of detail, a common approach was used to give a test report a quality rating on the basis of several highly subjective criteria; however, weighted average EFs generated in this way are not meant to reflect data precision or to be used for a refined risk analysis. The 95% upper confidence limit (UCL) of the unknown population mean was used in this study to account for the uncertainty in the EF test data. Several parametric UCLs were computed and compared for multiple welding EFs associated with several mild, stainless, and alloy steels. Also, several nonparametric statistical methods, including several bootstrap procedures, were used to compute 95% UCLs. For the nonparametric methods, a distribution for calculating the mean, standard deviation, and other statistical parameters for a dataset does not need to be assumed. There were instances when the sample size was small and instances when EFs for an electrode/process combination were not found. Those two points are addressed in this paper. Finally, this paper is an attempt to deal with the uncertainty in the value of a mean EF for an electrode/process combination that is based on test data from several laboratories. Welding EFs developed with a defined level of confidence may be used as input parameters for risk assessment.

IMPLICATIONS

The EFs with associated confidence limits that were developed and summarized in this paper will provide improved emission estimates from welding operations for process- and facility-specific applications. They can serve as another tool for developing emission inventories and generating input data for risk analysis. The factors can also be used to better estimate emissions for similar welding operations in which data are missing or unavailable.

INTRODUCTION

Metal welding is a common unit operation in a manufacturing environment. This activity generates fumes that contain potentially toxic compounds such as chromium (Cr), hexavalent Cr (Cr(VI)), manganese (Mn), nickel (Ni), and lead (Pb). Environmental agencies in the United States and abroad have set exposure limits to protect welders and have developed tools for estimating risk to individuals beyond a facility's fence line. In the absence of specific emission measurements, emission factors (EFs) have been used to predict welder exposure[1] and to estimate emission rate and release characteristics.[2]

The primary objective of this paper is to present an overview of the procedures developed for deriving welding EFs that can be used for performing residual risk analysis. Some of the factors that were responsible for the observed variability in the test EFs used for the statistical analysis included parameters such as welding current and voltage; welding speed; and electrode polarity, sampling methods, and analytical techniques. This paper will focus on Cr and Cr(VI) emissions from various electrodes and welding processes.

PROCESS AND MATERIAL VARIABILITY

The objective of welding is to achieve a deposit that has similar and, when possible, superior mechanical, physical, and chemical properties to that of the base metal (substrate). This is achieved by using the appropriate welding process, which could be manual, semiautomatic, or automatic. The welding operating conditions used in practice are most often those recommended by the manufacturer of the welding electrode.

Using fume chamber EF test data that were publicly available, EFs with a 95% upper confidence limit (UCL) of the mean were developed for mild steel and stainless steel electrodes that were used in conjunction with several commonly used arc welding processes,[3,4] which are briefly described in this paper.

- Shielded metal arc welding (SMAW) is sometimes referred to as manual arc or stick welding. The stick electrodes used in this process consist of core rods, which are coated (covered) with materials that generate gases as they are consumed. The core rods conduct the electric current to the arc, and the gases and molten slag produced during welding protect the solidifying weld metal from contaminants (e.g., oxygen and nitrogen) in the air. Various mild steel electrodes are used, including E1010, E6011, E7018, E7024, and E11018. Low-alloy steels are designated with a suffix, such as A1 or C1 (e.g., E7010-A1). Several stainless steel electrodes are also used with this welding process, including E308, E309, E310, and E316 electrodes, and they are often designated as E310-15 or E310-16. The first three digits of the designation refer to the electrode's composition, and the suffix portion refers to operational-related parameters. The first number after the hyphen (e.g., E310-"1"6) indicates the position(s) the electrode can be used, whereas the second number (e.g., E310-1"6") indicates the type of welding current and charge on the electrode.

- Gas metal arc welding (GMAW) is a semiautomatic process sometimes referred to as metal inert gas (MIG) welding when the shielding gas is helium, argon, or oxygen; or as metal active gas (MAG) arc welding when the shielding gas is carbon dioxide (CO_2) or another reactive gas. The composition of these solid electrodes will vary depending on the electrode's classification. The electrodes for mild steels include the E70S (e.g., E70S-3), ER70-S, and ER100 series. For welding stainless steel substrates, electrodes such as ER309-15 are used. The "R" in the designation shows that the electrode is in the form of a wire on a spool and not a stick-type electrode.
- The flux core arc welding (FCAW) process comes in two types of shielding. The first is self-shielding FCAW, in which the molten pool of metal is protected by the gas evolved by the decomposition of a flux within the tubular electrode because of the effect of the arc. The second type includes additional shielding gas that is externally supplied. The electrodes used for welding mild steels include the E70T and E71T series.
- In the submerged (metal) arc welding (SAW) process, the arc is submerged under a blanket of flux, which ends up covering the final weld deposit. The electrode is a solid, uncoated wire fed continuously into the mound of flux; the wire is consumed at the tip and contributes to the molten metal beneath the layer of molten slag produced by the melted flux. Cored wire electrodes in the SAW process included electrodes such as EM12K and ER309.
- Gas tungsten arc welding (GTAW) is also referred to as tungsten inert gas (TIG) welding. Gas shielding is required to protect the nonconsumable material; therefore, the level of fumes generated is low and comparable to that of SAW.

Results from a 1991 survey showed that the breakdown of welding operations was 45% SMAW, 34% GMAW, 17% FCAW, and 4% SAW; however, more recent trends show a decrease in SMAW usage in an effort to reduce the level of metal fume (e.g., Cr, Cr(VI)) emissions.

FUME GENERATION

The mass of consumable electrode converted to particulate matter (PM) may vary from 0.4 to 2.6%.[5] The amount of metals emitted by different rods depended on the characteristics of the metal welded and the welding process variables.

The release of metal pollutants from welding can be estimated from knowledge of the mass of electrode consumed and of the EF for the welding process/electrode combination. For example, the EF for Cr is a function of the fume generation rate (FGR) and is calculated as follows:

$$\begin{aligned} \text{EF (Cr)} &= \text{FGR (g fume/g electrode consumed)} \\ &\quad \times \text{ \% Cr in fumes} \end{aligned} \tag{1}$$

Several factors affect FGR, including the current, arc voltage, travel speed, and operating electrode angle. Other factors include the composition of shielding gas and the electrode composition, including the coatings. A recent survey of the studies on arc welding showed that SMAW and FCAW had higher fume-generating potentials than GMAW.[6] This general trend is also supported by a study aimed at evaluating Cr(VI) exposure levels in the shipbuilding industry.[7] In both of these studies, the fume levels for GTAW and SAW were much lower. These lower levels were attributed to the low current used during these welding processes; however, the fume-generation characteristics of different electrodes are expected to vary, depending more on the electrode flux composition for SMAW and FCAW and less on the sheath composition.[8]

Fume generation is a function of current and voltage, which affect the mode of droplet transfer. In the globular-spray transition regime, FGR (g/min) is low. When shielding gases such as CO_2 are used, larger particles are formed than those formed when the shielding gas is argon, resulting in more fumes. The mode of droplet transfer is less affected by the current and voltage because of the lack of globular-spray transition when CO_2 is used for shielding.[9] According to this and similar studies, the droplet-transfer mode can explain why SMAW and FCAW produce larger particles and create more fumes than GMAW.

COMPOSITION OF CR AND CR(VI) IN FUMES

The composition of the fumes depends on the electrode composition, among other parameters. Albert[10] showed for GMAW/stainless steel that the more volatile fume components, such as Cr and Mn, varied with voltage, reaching a maximum in the spray mode (~35 V). When sodium or potassium was used as a binder in electrode coatings, large amounts of Cr(VI) were formed, amounting to 36–100% of total Cr in SMAW/stainless steel fumes; however, using a lithium or organic binder resulted in lower amounts of Cr(VI)[11] In another study that also involved stainless steel electrodes, the Cr(VI) content was inversely proportional to the CO_2 in shielding gas, and for welding of stainless steel and GMAW without shielding gas, the welding mode influenced the Cr(VI) concentration.[12] In this study, Hewitt and Madden indicated that Cr(VI) for stainless steel was highest during short-circuit transfer (12–18 V) and lowest in spray mode (≥30 V). The level of Cr in Albert's study was high at the start of the short-circuit transfer mode (10–15V) but decreased with voltage to reach a maximum value (35–38 V).[10] The proportion of Cr(VI) to trivalent Cr may be influenced by other fume components such as iron (Fe), sample collection and preparation methods using acidic solutions (pH <0.5), and the use of dry filters.[13]

Mortazavi[14] believed that ozone (O_3) outside of the welding arc hot region was a contributing factor to the formation of Cr(VI) in the fumes. Adding 1% of magnesium (Mg), 1% of zinc (Zn), and 1% of aluminum (Al) resulted in O_3 reductions of greater than 98%, except for Al, in which the reduction was only 27%; however, only 1% of Zn reduced the Cr(VI) to a negligible amount. The other two additives considerably increased the amount of Cr that formed. The composition of flux-cored electrodes will vary from one manufacturer to another, and this brief exposition can help us understand the variability of the constituents (e.g., Cr(VI)) in fumes.

PARTICLE SIZE

Jenkins, Pierce, and Eager[15] studied the particle size distribution of FCAW and GMAW fumes and found that total fumes had at least two size modes on the basis of results obtained using a cascade impactor. In their study, most of the agglomerated particles were smaller than 1 μm. In Kura's study,[7] the fine fraction was made up of agglomerates less than 0.52 μm and the coarse fraction was greater than 3.52 μm; approximately 80% of the Cr(VI) concentration for GMAW/stainless steel was in the fine particle size range.

APPROACHES FOR DEVELOPING EFs

Four methods for estimating EFs were presented in a guide published in 2003 by the American Welding Society (AWS).[16] Annex A presented EFs for commonly used electrodes in arc welding and included values of the percentage of electrodes converted to fumes and the percentage of several elements in fumes (e.g., Fe and Mn). The concentration of total Cr and Ni in fumes from welding stainless steel was only provided for SMAW and GMAW.

A National Shipbuilding Research Program (NSRP) 1995 report[17] summarized information about EF development and derivation. It included EFs developed for the National Steel and Shipbuilding Company (NASSCO). The master set of EFs developed by Dr. Bell was used as the starting point. It was compiled for several electrodes (E316, E308, E309, and Inconel 625) and included the following: percent electrode converted to fumes, percentage of Cr in fumes, percentage of Cr(VI) in fumes, and percentage of Cr(VI)/Cr in fumes.[17] The average data for SMAW and GMAW are shown in Table 1. They concluded from an analysis of the data that there was no direct proportionality between the fume composition of Cr and Ni to that in the electrode used. For example, in 308L-16, Cr represented 18.7% of the solid electrode content, but the Cr in the fumes only amounted to approximately 5.66%. Therefore, they assumed an average proportionality to populate missing data along the rows of electrodes, and, where data were missing, the average value of a column of data was used to fill in the missing points in that column. The Cr(VI) EF (based on the data in Table 1) for SMAW is 2.49×10^{-4} g Cr(VI)/kg electrodes consumed and for GMAW is 0.303×10^{-4} g Cr(VI)/kg electrodes consumed.

This dataset was subsequently expanded by the California Air Resources Board (CARB) to include information from two AWS reports. The CARB data showed that the average Cr(VI)/Cr ratio data were approximately 63% for the SMAW process and approximately 5% for the GMAW process. Also, the expanded data showed that the concentration of metals in the fumes was higher for those electrodes that had a higher metal content, especially for metals with a lower melting point.[17]

EFs IN EPA'S AP-42 REPORT

The AP-42 report[2] is being used by state and local air quality control agencies throughout the United States as a source of EFs for electric arc welding and other emission sources. The AP-42 report only addressed particulate air pollutants from welding and assumed that fume particles from welding are ≤10 μm in diameter (PM_{10}). The AP-42 chapter on welding was last updated in the mid-1990s.[2]

The AP-42 report presented PM_{10} EFs (g/kg) for SMAW, GMAW, FCAW, and SAW. It also contained information on the percentage of selected metals in welding fumes, such as Cr, Cr(VI), Ni, and Pb. The report did not include similar information on gaseous pollutants such as O_3, CO_2, and carbon monoxide (CO), which were generated during metal arc welding. Some of these gaseous compounds are known today to have a bearing on the amount of Cr(VI) in welding fumes.

In the AP-42 report, the average EF for PM_{10} pertaining to a welding process/electrode type represents the (arithmetic) weighted average of the data points. The weighting was based on the number of tests (replicas) performed in each of the 12 primary reports referenced in Tables 4–16 in the AP-42 report.[2] Each EF was provided with a quality rating that is based upon a combination of the number of test reports averaged and the level and quality of each of the primary test reports. The AP-42 report contained limited information on Cr(VI)

Table 1. NASSCO's Cr and Cr(VI) average values (from Tables 14.2 and 14.3 in Bells' master dataset).[17]

Welding Process	% Cr in Electrode	% Electrode to Fumes	% Cr in Fumes	% Cr(VI) in Fumes	% Fumes to Electrode Cr	% Cr(VI)/Cr in Fumes
SMAW	19.6	0.626	5.61	3.95	28.6	70.8
GMAW	19.4	0.413	10.7	0.620	54.6	6.84

Notes: Dataset for SMAW (14 values) and GMAW (10 values); dataset values are likely to be arithmetic averages of test values.

EFs WITH AN UPPER CONFIDENCE LEVEL

EFs that were developed in the past were not intended to be used in risk assessments. They were developed for use as source-specific emissions estimates for area-wide emissions inventories, permit applicability applications, and for the determination of permit fees.[2] However, over time, EFs were applied to a wide range of uses for which they were not intended. To address some of the adverse implications associated with the use of the arithmetic mean, this paper provides one alternative that may address the effects of high variations of test data and the different number of replicates used to determine the mean. New EFs with a 95% UCL of the mean were developed after screening the available sources of EF data. The sources used are listed below.

- Individual test runs were obtained by going back to the 12 primary documents referenced in Table 4–16 of the AP-42 report.[2] Some of these references provided EFs based on one test run; however, on average, three to six replica (repeat) runs were reported. In one reference, more than 15 runs were performed to generate an average EF. The AP-42 report did not include EFs for E309 and for many of the alloy steels currently being used.
- The ESAB Welding and Cutting Products (ESAB) test results in the Welding Fume Analysis study involved E309 and three welding processes (SMAW, GMAW, and FCAW).[18]
- The NSRP report 0574,[19] NSRP report 0587,[20] and other related documentation provided the appropriate single data points.
- The CARB 2004 report, "Improving Welding Toxic Metal Emission Estimates in California" only provided single data for Cr(VI).[21,22]

To determine the 95% UCL of the mean for either stainless steels or mild steels when sufficient EF data values were available, a combination of tools was used to test for the appropriate parametric distribution (i.e., normal, lognormal, or gamma)[23]:

- Graphical quantile-quantile (Q-Q) plot and histogram
- Shapiro–Wilks test (sample size, $n \leq 50$) (normal and lognormal tests)
- Kolmogorov–Smirnov (K-S) test (gamma tests)

In computing the 95% UCL of the mean, the goodness-of-fit tests (Q-Q plots) for normality, lognormality, and gamma distribution were first performed. When these data were normally (or symmetrically) distributed, the Student's *t* test statistics were selected to represent the 95% UCL of the mean. The approximate symmetry was also evaluated from the histogram of the dataset.

For positively skewed datasets that followed a gamma (or approximate gamma) distribution, the 95% UCL of the mean was selected based on the gamma distribution. When none of these models represented the dataset, we compared the results of several nonparametric statistical methods (i.e., bootstrap and Chebyshev) before selecting the 95% UCL of the mean, relying on the ProUCL recommendations. When the UCL value exceeded the value of the highest point in the dataset, the next lowest 95% UCL value was selected.

Stainless Steels

The stainless steel EFs for Cr and Cr(VI) were grouped by welding process. These data that we used consisted of single data values.

Table 2 shows the 95% UCL of the mean for Cr and Cr(VI) for the stainless steel data. We assumed that the

Table 2. Proposed EFs for Cr and Cr(VI) for stainless steel electrodes.

				Statistics				
No.	Metal in Fumes	Welding Process	Rod Type	Mean (g/kg)	Maximum (g/kg)	Sample Size	95% UCL (g/kg)	Comments
1	Total Cr	SMAW	E308/E316	0.741	1.2	14	0.883	Student's *t* test
			E309	0.64	0.86	7	0.803	Student's *t* test
			All data	0.709	1.2	21	0.811	Student's *t* test
		GMAW	E316	1.03	1.3	3	7.72	Assumed normal distribution
			E309	4.6	6.51	4	7.61	Modified *t* test UCL (adjusted for skewness)
			All data	3.07	6.51	7	5.82	Bootstrap *t* test
		FCAW	E316	2.45	3.04	2	3.0	Assigned UCL for all data
			E309	2.22	2.86	4	3.30	Modified *t* test UCL (adjusted for skewness)
			All data	2.30	3.04	6	3.0	Student's *t* test
2	Cr(VI)	SMAW	E308/E316	0.175	0.353	18	0.20	Student's *t* test
			E309	0.092	0.163	7	0.141	Student's *t* test
			All data	0.15	0.228	25	0.176	Student's *t* test
		GMAW	E308/E316	0.0215	0.0497	13	0.0284	Student's *t* test
			E309	0.0475	0.0665	4	0.0801	Student's *t* test
			All data	0.0277	0.0665	17	0.0392	Approximately gamma
		FCAW	E316	0.0559	0.0707	3	0.105	Assumed normal distribution
			E309	0.0312	0.122	10	0.0763	95% Chebyshev (Mean, SD)
			All data	0.0306	0.0707	13	0.0748	95% Chebyshev (Mean, SD)

E308 and E316 (14 data values) could be combined because these types of electrodes are only used to weld stainless steel substrates, and the EFs (dataset) for both electrodes overlapped. The seven data points for E309 were first treated separately because this type of electrode could also be used to weld mild steel substrates. We took this precaution because the substrate welded can contribute metals to the fumes. When this occurs, the substrate contribution would be on the order of 5% or less.[24]

Cr. Because it would be advantageous to have one UCL that would apply to this classification of electrodes, it was decided to combine all of the data for electrodes E308, E309, and E316. The 95% UCL of the mean for Cr from SMAW was 0.811 g/kg (Student's *t* test). We believe that this value would also be representative of other stainless steel electrodes, such as E347 and E429, because the level of Cr in these electrodes is comparable to that in the electrodes used in this analysis. The same approach was followed to determine the corresponding UCL EF values for GMAW and FCAW.

GMAW. In the case of GMAW, the NSRP data for E316 were of the same order of magnitude as that for the ESAB ER309L electrode (one data point). The Cr levels in the fumes for E309 (three runs) in the NSRP 0587 report were consistently higher than for the E316 runs. For FCAW, the Cr level in the NSRP 0587 report was slightly higher than that in the ESAB report. In both reports, the Cr level in fumes was less than 1% by mass of fumes, which is reasonable considering that the Cr level in stainless steel electrodes can exceed 13% of the mass of rod. However, the Cr level can reach up to 35% by mass in the NSRP 0574 report,[19] which is approximately 10% higher than the maximum assumed to be the norm.

Cr(VI). The stainless steel data points for Cr(VI) were more consistent, which is apparent from the results shown in Table 2. For SMAW, the dataset was collected from the NSRP 0587 report (18 data points), the CARB report (4 data points), the ESAB report (1 data point), and the AP-42 report (2 data points). The EF for SMAW on the basis of these data points was 0.176 g/kg. For GMAW, the dataset came from the NSRP report (6 data points), the CARB report (10 data points), and the ESAB report (1 data point). The FCAW results were drawn from the NSRP report (six data points), the CARB report (3 data points), and the ESAB report (1 data point).

Mild Steels

Most of the welding studies reviewed for mild steel welding operations did not report the amount of Cr or Cr(VI); however, mild steels are believed to contain less than 0.5% Cr by mass according to material data sheets listed by several major U.S.-based electrode suppliers. Specific electrode data indicate that the Cr content for E7018 can vary from 0.15 to less than 0.03% by mass; E8018 up to 1% Cr; and E11018 to approximately 0.4% Cr. These Cr levels are much lower than in stainless steel electrodes, in which Cr content normally varied between 16 and 25%, but in some cases exceeded 30% (by mass). However, it was important to have EFs for the different process electrode combinations that involved mild steel electrodes because most industrial operations use more mild steel than stainless steel. Table 3 contains a summary of the proposed Cr and Cr(VI) EFs for mild steel welding operations.

Cr. First, an EF for SMAW was estimated by multiplying the Cr EF, which we had previously derived for SMAW/(E308 and E316) = 0.833 g/kg, by the ratio of the maximum level of total Cr in mild steel and what we assumed to be a representative average [(16% + 25%)/2] level of Cr in stainless steel (see eq 2):

$$(0.883 \text{ g/kg}) \times (0.5\%/20\%) = 0.0221 \text{ g/kg} \qquad (2)$$

As noted in Table 3, there are two EF data values for SMAW/(E7018 and E7028). The maximum value 0.0117 g/kg was comparable to the Cr level of 0.0221 g/kg that was estimated above. Therefore, we selected the maximum test data point as the default 95% UCL EF, as shown in Table 3. We also used the maximum value for GMAW as the default value for the UCL. In the case of FCAW/(E70-T and E71-T), we had 40 EF data values, which were adequate for computing the 95% UCL of the mean. The 95% Chebyshev (mean, SD) was chosen to represent the UCL value.

In the case of the Cr dataset for FCAW, it was believed that electrode E-770,[20] which is listed in Table 3, was TM-770 by Tri-Mark,[25] which was equivalent to the AWS series E71T-1M, and E71T-12MJ. Because the EFs for the test data that corresponded to the TM-770 or E71T-XM series were inexplicably higher than for FCAW/(E70T and E71T), a 95% UCL EF was proposed for the E70/E71 series and another 95% UCL EF for the series that contained an "M." The 95% UCL for the E71T-XM series was based on the Student's *t* test.

Cr(VI). Because we did not have EFs for Cr(VI), it was assumed that the EF for Cr(VI) was a defined fraction of total Cr and that fraction was dependent on the welding process. To obtain that conversion ratio (i.e., Cr(VI)/total Cr), we used the fume composition data in Table 5 of the "Chromium in Stainless Steel Welding Fumes" report.[24] This report summarized the low- and high-fume composition values of Cr and Cr(VI) for SMAW, GMAW, FCAW, and SAW. For example, the fume level of Cr for SMAW varied between 1 and 10%, and the level for Cr(VI) varied between 0.5 and 6%. Therefore, the ratio of the average levels was 55% for SMAW. Using the same procedure, the ratio of Cr(VI)/total Cr was 5% for GMAW, 10% for FCAW, and 0.05% for SAW.

Alloy Steels

The electrodes for alloy steels contain higher levels of Cr, Ni, or Mn than the stainless steels or mild steels listed in Tables 2 and 3. Because the test data on EF for alloy steels were limited or not available in some cases, a different approach was developed for estimating an UCL EF for these welding electrodes. An UCL EF value was derived by following several steps.

Table 3. Proposed emission factors for Cr and Cr(VI) for mild steel electrodes.

No.	Metal in Fumes	Welding Process	Rod Type	Statistics			
				Mean (g/kg)	Maximum (g/kg)	Sample Size	95% UCL (g/kg)
1	Cr	SMAW	E7018/28	0.0109	0.0117	2	
			E11018	ND	ND	0	
			All data			2	0.0221
			(Default)				0.0117
		GMAW	E70S (3–6)	0.00228	0.00378	3	
			E70S (6)	0.0719	0.0801	2	
			All data			5	0.0801
			(Default)				0.0801
		FCAW (TM770)	E70T/E71T	0.00307	0.0345	40	0.00667
			E71M			3	
			E71T-1M			2	
			All five data points	0.0416	0.0624	5	0.0594
2	Cr(VI)	SMAW	E7018/28	ND	ND	0	
			E11018			0	
			Calculated: Cr EF and 55% Cr (VI)/Cr			–	0.0121
			(Default)				0.00643
		GMAW	E70S (3–6)	ND	ND	0	
			E70S-6		0.0041	1	
			All data			1	0.0041
			(Default)				0.0003
		FCAW	E70T/E71T	ND	ND	0	0.0007
			E71M	0.02666	0.0508	3	
		FCAW (TM770)	E71T-1M	0.00255	0.00265	2	
			All five data points			5	0.0336
			(Default)				0.0059

Notes: ND = no data; – = calculated value.

(1) The PM_{10} EF from Tables 4–15 of the AP-42 report was selected for SMAW (18.2 g/kg), GMAW (3.9 g/kg), FCAW (9.1 g/kg), and SAW (0.05 g/kg). These values represent the alloy with the highest EF for a given welding process. For SMAW, we elected not to use ECoCr-A (27.9 g/kg) (Co = cobalt) because of its low usage and decided instead to use the second largest value (18.2 g/kg).

(2) The percentage of Cr metal in fume was estimated using the following equation by McLiwain and Numeir,[26] which were derived using data for several stainless steel and alloy steels (see eq 3).

$$\%\ \text{Cr in fume} = -0.31 + [0.66 \times (\%\ \text{Cr in electrode})] \quad (3)$$

Equation 3 was not used when the amount of Cr in the electrode was less than 2% by mass. Instead, the slope 0.66 was used to estimate the amount of Cr in the fume.

As an illustration, if an alloy steel applied with SMAW contained 15% Cr by mass and we entered this information in eq 3, the amount of Cr in fumes would be 9.59% by mass. The Cr EF for this electrode would then be derived using eqs 4 and 5 as follows:

$$\text{EF for Cr} = (18.2\ \text{g/kg}) \times (0.0959) = 1.75\ \text{g/kg} \quad (4)$$

In addition, the EF for Cr(VI) would be 55% of the Cr EF as was assumed above for SMAW in the section entitled *Mild Steels*.

$$\text{EF for Cr(6)} = 0.55 \times 1.75\ \text{g/kg} = 0.96\ \text{g/kg} \quad (5)$$

A default EF for Cr from SAW can also be calculated by multiplying the candidate total PM_{10} generation rate (0.05 g/kg) from Table 4-18 in AP-42[2] by the composition of Cr in the fume. The product is a much lower UCL EF than for either SMAW or FCAW. The amount of Cr(VI) for SAW is obtained by multiplying the EF for Cr by 0.05%, which is the Cr(VI)/total Cr ratio.

Lastly, the original data points used to calculate the 95% UCL EFs are tabulated in ref 27. The document also contains UCL EFs when test data were not available. Some of these values may need to be revised as more specific Cr data for an electrode become available.

DISCUSSION

The release of metal pollutants such as Cr and Cr(VI) from welding operations can be calculated from knowledge of the FGR (g/kg) and the fume composition. We have identified many operating parameters that influenced fume generation and have tried to explain why FCAW exhibited the highest fume-generating potential, whereas

GMAW exhibited the lowest of the three more predominantly used welding processes. This trend was observed in chamber tests[2] and in a study aimed at evaluating Cr(VI) exposure levels from welding in shipyards.[7] The low FGR potential of SAW and GTAW was also highlighted. A review of the studies in the literature showed that the FGR (g/min) potential for stainless steel electrodes and the mild steel electrodes were sometimes comparable. This should not be surprising considering the number of parameters that came into play, including current, voltage, travel speed, shielding gas, and electrode composition. In general, fume generation increased with current and power applied during welding. It was also influenced by the type of current (i.e., pulsed or steady state).[28] However, it is difficult to determine the effect of welding parameters such as voltage and current on the FGR because for each welding current there is a corresponding voltage that is selected to give the lowest FGR condition.[24,29]

Sample size is an important parameter in determining confidence limits. It is generally accepted that the larger the sample size, the more confidence we have that the results of a statistical analysis are accurate. The size of a dataset for a process/electrode combination varied from one metal to another. As shown in Table 2, the Cr dataset for SMAW/stainless steel consisted of 21 data points. The dataset was normally (or symmetrically) distributed, and the Student's *t* test statistics were selected to represent the 95% UCL of the mean. Although the Cr FCAW/stainless steel dataset was six points, the Student's *t* test statistics provided adequate coverage at the 95% UCL; the Bootstrap *t* test statistics provided better coverage for Cr GMAW/stainless steel than the Student's *t* test statistics for this small dataset (seven data points). These conclusions were based on the Monte-Carlo-generated data in *ProUCL Version 3 User Guide* (Appendix A).[30]

In the case of Cr(VI), we had had a minimum of 25 data points in a dataset: the SMAW/stainless steel dataset was normally (or symmetrically) distributed, and the Student's *t* test was selected to represent the 95% UCL of the mean. The Bootstrap *t* test statistics provided a slightly higher coverage for this dataset, which was determined to be insignificant. The GMAW/stainless steel dataset (17 data points) was gamma-distributed based on a gamma Q-Q plot, with $r = 0.969$. Because the bias-corrected estimate of the shape factor (k) of the gamma distributed dataset k hat, was 1.87 (i.e., $k > 0.5$) the 95% UCL value of the approximate gamma distribution was selected. The FCAW/stainless steel dataset was not normal, gamma, or lognormal at the 5% significant level. The 95% Chebyshev (mean, SD) UCL was selected, which is a nonparametric UCL. The 95%UCL value provided adequate coverage for this dataset, which was moderately skewed positively. In this case, all of the bootstrap methods tested using the FCAW/stainless steel dataset provided coverage below the 95% UCL of the mean. These results may be attributed to the combination of a relatively small sample size and the parameters of the gamma distribution.[30]

The new EF values presented here may change in the future as a result of improvements in sampling and test methodology that inhibits the conversion of Cr(VI) and has a lower limit of detection. More testing on mild steels may be needed to determine the contribution to Cr(VI) emissions.[22] Lastly, the 95% UCL of the mean of these individual EF data points provides a reasonable confidence that the true average value is not underestimated.

CONCLUSIONS

The 95% UCL of the mean EFs for stainless steel and mild steel was derived when there were sufficient EF data to perform the necessary tests and calculations. A procedure for calculating EFs with an upper level of confidence was also developed for alloy and other steels when no EF data were available. It is hoped that this document will help promote a discussion that will lead to a refinement of the 95% UCL EF values and the methodology for calculating EFs when no data are available.

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