DEVELOPMENT OF DEFAULT WELDING EMISSION FACTORS

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BACKGROUND

This documentation supplements the San Diego County Air Pollution Control District (District) Welding Operation Emissions Calculation Procedures.

Emissions associated with welding activities may pose a health risk to the public and therefore the District has created methodologies to calculate emissions from these processes. There are multiple methodologies for estimating emissions, including Toxic Air Contaminants (TACs), from welding processes. The key variables in estimating emissions from welding are the type of rod and pollutant specific emission factor. The following approach details the District's current methodology and emission factors used for calculating emissions.

The District has ranked the following emission factor sources and recommends the use of this overarching hierarchy, as it provides the representative emission estimates for any given rod and pollutant combination. In cases where AP-42 factors were incorporated into welding specific studies, the emission factors found in the welding specific studies may have been adopted as they were found to be more comprehensive.

1. AP-42 Section 12.19 Electric Arc Welding: Emission factors reviewed and published as described in AP-42 Section 12.19 were used when available. Not all rods and pollutants are presented in AP-42 Section 12.19.

2. Welding Specific Studies: Emission factors from studies specific to welding processes, including those completed by Dr. Richard Bode (1993), with industry in San Diego County (Bell, NASSCO, 1995), and from Air & Waste Management Association (Serageldin & Reeves, 2012) were used when available.

3. Material Safety Data Sheets (MSDS): If emission factors were not available from AP-42 Section 12.19 or welding specific studies, then MSDS were used to quantify emission factors. This is the least favorable method, as MSDS can vary by manufacturer.
    a. District Welding Study MSDS – Survey sent to facilities in San Diego County in 2020 to collect MSDS and welding information.
    b. Historical Welding MSDS – MSDS submitted to the District, either for permitting or emission inventory purposes.

The District will update this document as new studies and reports become available from Federal, state, local air pollution control programs, and industry, as appropriate.

EPA AP-42 WELDING ROD COMPOSITION AND EMISSION FACTORS

The District's evaluation of welding rod emission factors relied primarily upon the emission factors published in AP-42 by the EPA in 1995. The thirty-two (32) welding rods defined in AP-42 Section 12.19 and listed under the District's Toxic procedures are as follows:

Table 1: District and AP-42 Specified Rods[1,2]

1 - SUBMERGED ARC WELDING (SAW), EM12K
2 - FLUX CORE ARC WELDING (FCAW), E70T
3 - Flux Core Arc Welding (FCAW)-E 71T
4 - Flux Core Arc Welding (FCAW)-E 110
5 - Flux Core Arc Welding (FCAW)-E 308LT
6 - Flux Core Arc Welding (FCAW)-E 316LT
7 - Flux Core Arc Welding (FCAW)-E 11018
8 - Gas Metal Arc Welding (GMAW)-E 70S
9 - Gas Metal Arc Welding (GMAW)-E 308L
10 - Gas Metal Arc Welding (GMAW)-ER 316
11 - Gas Metal Arc Welding (GMAW)-ER 1260
12 - Gas Metal Arc Welding (GMAW)-ER 5154
13 - Gas Metal Arc Welding (GMAW)-ER NiCrMo

[1] https://www.sdapcd.org/content/sdc/apcd/en/engineering/Permits/Engineering_Emissions_Inventory/Welding_Calc.html

[2] https://www.epa.gov/sites/production/files/2020-11/documents/c12s19.pdf

14 - Gas Metal Arc Welding (GMAW)-ER NiCu
15 - Shielded Metal Arc Welding (SMAW)-E 308
16 - Shielded Metal Arc Welding (SMAW)-E 310
17 - Shielded Metal Arc Welding (SMAW)-E 316
18 - Shielded Metal Arc Welding (SMAW)-E 410
19 - Shielded Metal Arc Welding (SMAW)-E 6010
20 - Shielded Metal Arc Welding (SMAW)-E 6011
21 - Shielded Metal Arc Welding (SMAW)-E 6012
22 - Shielded Metal Arc Welding (SMAW)-E 6013
23 - Shielded Metal Arc Welding (SMAW)-E 7018
24 - Shielded Metal Arc Welding (SMAW)-E 7024
25 - Shielded Metal Arc Welding (SMAW)-E 7028
26 - Shielded Metal Arc Welding (SMAW)-E 8018
27 - Shielded Metal Arc Welding (SMAW)-E 9018
28 - Shielded Metal Arc Welding (SMAW)-E 11018
29 - Shielded Metal Arc Welding (SMAW)-E CoCr
30 - Shielded Metal Arc Welding (SMAW)-E 14Mn-4Cr
31 - Shielded Metal Arc Welding (SMAW)-E NiCr
32 - Shielded Metal Arc Welding (SMAW)-E NiCrMo

Emissions for rods are calculated on a per welding process basis and may use a combination of factors from historical documentation including: “fume generation rate” (FGR) from EPA AP-42 or CARB recommendation; “fume correction factor” (FCF) from NASSCO studies; and hexavalent chromium conversion factor from AWMA studies. The factors specific to each welding process are specified below:

Table 2: Welding Factors for Emissions Calculations[3,4]

Welding Process	Fume Generation Rate – FGR (lbs fume/lb rod)	Fume Correction Factor – FCF	Hexavalent Chromium Conversion Factor
GMAW/MIG/TIG	0.01	0.5464	0.05
SMAW	0.02	0.2865	0.55
FCAW	0.02	0.2865	0.10
SAW	-	-	0.0005
Unspecified	0.05	1.0	0.10

Those thirty-two (32) rods are considered “default” by the District because there exists FGRs and/or Hazardous Air Pollutant (HAP) emission factors for them in AP-42 Section 12.19. However, there are many cases where emission factors must be calculated using a combination

[3] https://www.sdapcd.org/content/dam/sdc/apcd/PDF/Toxics_Program/APCD_welding1.pdf
[4] https://www.tandfonline.com/doi/abs/10.3155/1047-3289.59.5.619

of their fume generation rate (FGR), fume correction factor (FCF), shown in Table 2, and rod compositions (Ci).

The equation for calculating an emission factor is as follows:

EF = FGR x FCF x Ci

EF = Emission Factor (lbs metal/lb rod rod consumed)

FGR = Fume Generation Rate (lbs fume/lb rod consumed)

FCF = Fume Correction Factor (lbs metal/lb fume)

Ci = Concentration of listed substance in each welding rod (%)

An additional factor is applied for calculating Emission Factor (EF) of Hexavalent Chromium (Cr (VI)) by using a Cr (VI) Conversion Factor, as shown in Table 2:

EF Cr (VI) = FGR x FCF x Ci (Total Cr) x Cr (VI) Conversion Factor

Emissions for different TACs or HAPs are determined using the following equation whether the EF used is default or calculated:

Ea (annual emissions) = Ua (lbs annual usage) x EF (lbs/lb rod)

Eh (hourly emissions) = Uh (lbs hourly usage) x EF (lbs/lb rod)

WELDING SPECIFIC STUDIES

HISTORICAL DEVELOPMENT OF DISTRICT EMISSION FACTORS

The District coordinated with both California Air Resources Board (CARB) and local industry (NASSCO) to review the American Welding Study (AWS) data to establish a welding emission calculation method for the District's emissions inventory program in early 1990's.

In a 1993 review of the AWS, CARB recommended that default fume generation rates and hexavalent chromium conversion ratios be applied when calculating welding emissions. NASSCO's consultant reviewed the AWS information in 1992 & 1995 and concluded that a "fume composition correction factor" was necessary to account for the nonmetallic portion of the released fumes.

The EPA also published Section 12.19 of AP-42 for "Electric Arc Welding" in 1995 and based their set of incomplete emission factors on AWS. Until more confirmation or representative test results became available, a combination of the above research and documentation was used by the District to quantify welding emissions.

STUDIES ON WELDING ROD EMISSION FACTORS – SMAW/GMAW

As the District has evaluated health risks associated with the use of different welding rods, for both permitting and emissions inventory for the Air Toxics "Hot Spots" programs, the emission calculations and factors described in this document were assessed for accuracy by reviewing recent studies. The research was done specifically on the emissions of hexavalent chrome and the relationships between and/or the effects different welding processes, rod types, and welding metals have on them.

The notable studies were a report from UC Davis[5] (UCD) and an entry from the Journal of Air and Waste Management Association**Error! Bookmark not defined.** (AWMA) – both studies referenced using EPA AP-42[6] AWS welding studies as the basis for their analyses.

The studies determined that, in general, emission factors from EPA AP-42 Section 12.19 were somewhat conservative for calculating welding emissions but useful for risk evaluation purposes. The studies presented differences within only certain rods and weld metals – namely there were significant studies performed on specific stainless steel and mild steel rods with enough data to justify the District's implementation of new emission factors. Additionally, alloy rods were also assessed in these studies with suggestions for new calculation methodology but there was not enough data to justify implementation at this time but consideration for changes will remain an open possibility for the future.

The rods in Table 3 and Table 4 below had new Total Chrome (Cr) and Hexavalent Chrome (Cr (VI)) emission factors (EFs) for stainless steel and mild steel rods, respectively, proposed by both UC Davis and the Journal of Air & Waste Management (AWMA). SMAW and GMAW factors proposed by AWMA were adopted by the District for use in calculating emissions. The studies did not propose changes to the current District annual/hourly emissions calculation method, fume generation rate(s), correction factors, or other metal emission factors but had suggested new hexavalent chrome conversion rates (see Table 2) which were also implemented.

Table 3: AWMA Total Chrome and Hexavalent Chrome EFs for Stainless Steel Rods**Error! Bookmark not defined.**

Metal	Welding Process	Rod Type	95% UCL (g/kg)
Total Cr	SMAW	E308/E316	0.883
	GMAW	E316	7.72
	FCAW	E316	3
Cr(VI)	SMAW	E308/E316	0.2
	GMAW	E316	0.0284
	FCAW	E316	0.105
Total Cr	SMAW	E309	0.803

[5] https://ww2.arb.ca.gov/sites/default/files/2021-07/report_0.pdf
[6] https://www.epa.gov/sites/default/files/2020-11/documents/c12s19_0.pdf

	GMAW FCAW	E309 E309	7.61 3.3
Cr(VI)	SMAW GMAW FCAW	E309 E309 E309	0.141 0.0801 0.0763

Table 4: AWMA Total Chrome and Hexavalent Chrome EFs for Mild Steel Rods**Error! Bookmark not defined.**

Metal	Welding Process	Rod Type	95% UCL (g/kg)
Total Cr	SMAW	E7018/28 E11018	0.0117
Cr(VI)		E7018/28 E11018	0.00634
Total Cr	GMAW	E70S (3-6) E70S (6)	0.0801
Cr(VI)		E70S (3-6) E70S (6)	0.0041
Total Cr	FCAW	E70T/E71T E71M/E71T-1M	0.00667 0.0594
Cr(VI)		E70T/E71T E71M/E71T-1M	0.0007 0.0059

STUDIES ON WELDING ROD EMISSION FACTORS – FCAW

FCAW EF BACKGROUND

As is with most welding rods, Flux-Cored Arc Welding (FCAW) composition and emissions will vary by electrode type, although all rod types can be categorized into two main categories, stainless steel and mild steel electrodes, and with or without additional shielding gas. Various pollutants are emitted from welding of FCAW rods, including but not limited to, Chromium (Cr), Hexavalent Chromium (Cr (VI)), Manganese (Mn), Nickel (Ni), Lead (Pb),

and Cadmium (Cd). The District has recently reviewed various reports and documents, such as research conducted by federal and state agencies, as well as scientific literature and reports to determine the best default emission factors for estimating emissions from welding of FCAW rods. The District reviewed multiple sources during evaluation of emission factors for FCAW welding rods, including:

- Development of Welding Emission Factors for Cr and Cr (VI) with a Confidence Level published by the Air & Waste Management Association (AWMA) (2009),
- National Shipbuilding Research Program (NSRP) 1995 report (including factors developed for General Dynamics National Steel and Shipbuilding Company (NASSCO)),
- Welding Fume Analysis Study by Elektriska Svetsnings – Aktiebolaget ((ESAB), an American Swedish industrial company and the world's largest producer of standard welding equipment) Welding and Cutting Products (2000),
- Improving Welding Toxic Metal Emission Estimate in California a California Air Resources Board (CARB) Report (2004),
- AP-42 Chapter 12.19 (1995)
- Developing Emissions Factors for Electrodes Commonly used within the Shipbuilding Industry for use in Regulator Reporting Procedures, Final Project Technical Report published by Concurrent Technologies Corporation (CTC) (2009)

The District reviewed and analyzed the raw data, including test reports, for these studies listed. For the AWMA study, the District reviewed the background document for the test data (*Shipbuilding and Ship Repair – Residual Risk – Proposed Emission Factors for Stainless Steels, Mild Steel, and Alloy Steels*) cited in their research paper as it was a compilation of external testing. Averaged test values listed in AP-42 Chapter 12.19 Tables 4-3 through 4-14 were used for cases when individual data was unavailable. It should be noted that the statistical analysis completed by the AWMA study is more comprehensive although does differ from the straight means described below. Please note that not all individual studies listed alone had previously been utilized by the District, however, after additional testing became available, it was found that the results were aligned and therefore all studies above were considered when reviewing emission factors for FCAW welding rods.

Based on the District's review of FCAW emission factors, and as stated in the AWMA paper, it is evident that use of shielding gas affects the fume generation rate (FGR) during welding. Therefore, the District completed supplementary review for comparison of FCAW welding emission factors which used additional shielding gas versus processes without added shielding gas, as FCAW has the potential to be welded with or without shielding gas by way of self-shielding through the vaporization of the flux core. When FCAW is welded without additional shielding gas, it is referred to as 'self-shielded'. For the purposes of this review, self-shielded rods will be referred to as being used without shielding gas.

FCAW WELDING USING SHIELDING GAS

A total of 73 tests of FCAW rods with additional shielding gases were reviewed from the sources listed above which included testing for various pollutants. Some studies suggest that FCAW rods 309 and 316 emission factors can be combined due to their shared use on stainless steel, this

was not verifiable by the District as there was a large enough difference between the two and therefore the District has determined that they should be separated.

Tables 5 and 6 below, are the straight averaged emission factors for stainless and mild steel rods, respectively, from all 73 tests, please refer to Appendices A and B for the full compiled list of test results.

Table 5. District averages of stainless-steel FCAW EFs using shielding gas (24 tests)

Rod Type	TSP EF (lb/lb)	Total Cr EF (lb/lb)	Cr(VI) EF (lb/lb)	Mn EF (lb/lb)	Ni EF (lb/lb)	Pb EF (lb/lb)	Cd EF (lb/lb)
E316	3.83E-01	2.45E-03	5.59E-05	1.69E-02	1.91E-01	--	--
E309	5.50E-02	1.23E-03	2.82E-05	1.99E-03	2.48E-02	8.61E-06	4.82E-06

Table 6. District averages of mild steel FCAW EFs using shielding gas (49 tests)

Rod	TSP EF (lb/lb)	Total Cr EF (lb/lb)	Cr(VI) EF (lb/lb)	Mn EF (lb/lb)	Ni EF (lb/lb)	Pb EF (lb/lb)	Cd EF (lb/lb)
E70T	--	2.33E-06*	--	1.13E-03	1.10E-05	--	--
E71T	--	2.09E-06*	--	1.07E-03	3.76E-06	--	--

*Assume 10% chromium conversion factor of total chrome to Cr(VI) (Ref 6, p. 623)

FCAW WELDING WITHOUT SHIELDING GAS

A total of 36 tests of FCAW rods with no additional shielding gases were reviewed from the same set of sources which also included testing for various pollutants. Tables 7 and 8 are the straight averages of data for stainless and mild steel rods, respectively, welded as FCAW without shielding gas.

Table 7. District averages of FCAW stainless-steel EFs without shielding gas (11 tests)

Rod	TSP EF (lb/lb)	Total Cr EF (lb/lb)	Cr(VI) EF (lb/lb)	Mn EF (lb/lb)	Ni EF (lb/lb)	Pb EF (lb/lb)	Cd EF (lb/lb)
E316	2.81E-01	5.36E-03	2.30E-04	9.68E-03	2.30E-01	2.94E-05	6.00E-06
E309	2.99E-01	2.07E-04	1.60E-04	4.21E-03	5.75E-03	6.45E-05	7.10E-06

Table 8. District averages of FCAW mild steel EFs without shielding gas (25 test)

Rod	TSP EF (lb/lb)	Total Cr EF (lb/lb)	Cr(VI) EF (lb/lb)	Mn EF (lb/lb)	Ni EF (lb/lb)	Pb EF (lb/lb)	Cd EF (lb/lb)
E70T	1.81E-01	2.66E-05	9.00E-06	2.14E-03	1.73E-03	5.01E-05	6.40E-06
E71T	5.51E-01	5.14E-05	3.87E-05	1.42E-02	3.15E-02	2.88E-04	--

FCAW W/ & W/O SHIELDING GAS DISCUSSION

Comparing information in Tables 5-8 above, where appropriate, it is clear that FCAW welding emission factors for metals are dependent on the application of shielding gas. Rods welded without shielding gas have higher emission factors than when shielding gas is applied and, as is the case of Cr (VI) and stainless steel, the difference can be as large as an entire order of magnitude.

Historically, the District has compared the emission factors of FCAW and Shielded Metal Arc Welding (SMAW) welding processes. This was reviewed again by using the new District FCAW emission factors and comparing them against the AWMA SMAW emission factors (which are still utilized by the District). Table 9 shows that stainless steel hexavalent chromium emission factors are similar between FCAW without shielding gas and SMAW.

Table 9. Comparison of District FCAW and AWMA SMAW stainless-steel Cr (VI) EFs

Electrode	Welding Process	Shielding Gas	Average	Cr(VI) EF (lb/lb)
E309/E316	FCAW	Yes	Straight	3.70E-05
E309/E316	FCAW	No	Straight	1.95E-04
E308/E316/E309	SMAW	Yes	95% UCL	1.76E-04*

* SMAW emission factor determined by AWMA was a statistical analysis of 25 data points (Ref 6, p. 622)

Data is limited on the amount of hexavalent chromium compared to total chromium in welding fumes but there is a general understanding that some portion of total chromium is being converted to hexavalent chromium; for consistency and reproducibility, the chrome conversion emission factors (see Table 6) are favored over the limited data until there is more representative data available and reviewed.

In summary, the District has determined that there are significant differences between FCAW emission factors when rods are welded with and without shielding gas. Similarly, the differences in emission factors between different welding rods themselves is significant and will need to be differentiated.

Moving forward, the District will be using the emission factors it adopted from our review of these studies as shown in Tables 5-8, and will consider additional references and applicable test data for consideration to add to these data pools in the future, as appropriate.

The District will continue to use EPA AP-42 along with historic NASSCO and ARB data for all total chromium and hexavalent chromium emission factors not included in Table 3 and Table 8 until new representative data, such as source tests or further studies, are available and reviewed.

DISCUSSION OF FCAW EF AND CURRENT AWS STANDARDS

The American Welding Society (AWS) sets standards and certifications for welding materials, welders and facilities where welding occurs. The District compared the current AWS certified

TAC content of each FCAW rod against the tested values found in the welding studies. Through this analysis, the District concluded the values published do not align with some of the test results of the National Shipbuilding Research Program (NSRP) Study, "*Emission Factors for Flux Cored Rod Used in Gas Shielding Processes"*(2000). Therefore, the District has created two sets of default emission factors for FCAW rods, one for facilities which use rods which are AWS certified and those which are not using these AWS certified standard rods.

DISTRICT WELDING ROD COMPOSITION AND EMISSION FACTORS

In 2020, questionnaires were sent to facilities to gather information about welding processes in San Diego County. The questionaries are meant to supplement data available from AP-42 Section 12.19 and welding specific studies. After review, it was evident that additional rods would need to be added to the District's database. The following rods were documented as being used at more than one facility, and not having data available in AP-42 or from the District's own references:

Table 10: New District Specified Rods (EPA AP-42 Unspecified)

33 – 4043
34 – 5356
35 – 309
36 – 347
37 – RN60
38 – RN67
39 – 4130
40 – 5554
41 – 5556
42 – 718
43 – 80S
44 – 90S
45 – 5786
46 – 9015
47 – ERTi-2
48 – INCO 62
49 – L-56

The rods listed in Table 10 had MSDS either provided or researched online to provide a chemical composition that could be used for emissions calculations. Multiple MSDS from these shared rods, those seen to be used at more than one facility, were used to find an average composition of TACs. Below are the chemical compositions:

Table 11: New District Specified Rod Chemical Compositions (AP-42 Unspecified)

Unspecified Rod	% Copper	%Manganese	% Nickel	% Total Chromium
4043	0.75%	0.30%		0.15%
5356		0.55%		0.37%
309		2%	13%	26.5%
347			10%	17.5%
RN60	25%	3.75%	67%	0.05%
RN67	65%	0.7%	30%	
4130	0.50%	0.60%	0.60%	2.70%
5554	1.00%	1.00%		0.20%
5556	0.10%	1.00%		0.20%
718	0.30%	0.35%	55.0%	21.0%
80S	0.35%	0.70%	2.00%	2.70%
90S	0.35%	1.20%	0.80%	5.00%
5786		1.00%	68.0%	6.00%
4643	0.30%	0.05%		
9015		0.85%		8.60%
ERTi-2	0%	0%	0%	0%
INCO 62	0.50%	1.00%	70.0%	17%
L-56		5.00%		

Emissions were calculated using equations listed in Section 1.1 for most welding processes (GMAW/SMAW/FCAW) using the factors from Table 2 as opposed to only one specific

process/rod combination like rods in Table 1. This was done for completeness and flexibility because there is no AP-42 data for these rods.

REFERENCES

1. *Compilation of Air Pollutant Emission Factors: Development of Particulate and Hazardous Emission Factors for Electric Arc Welding*; AP-42, Section 12-19; Revised Final Report: 1995

2. *Welding Fume Analysis Study*; ESAB Welding and Cutting Products; National Steel and Shipbuilding Company: San Diego, CA, 2000

3. *Emission Factors for Flux Cored Rod Used in Gas Shielding Processes*; NSRP 0587, NI-98-1, Subtask 43; National Shipbuilding Research Program: 2000

4. *Improving Welding Toxic Metal Emission Estimates in California*, Final Report; Prepared for the California Air Resources Board, Sacramento, CA, by University of California–Davis; Department of Civil and Environmental Engineering: Davis, CA, 2004

5. *Developing Emissions Factors for Electrodes Commonly used within the Shipbuilding Industry for use in Regulator Reporting Procedures*, Final Project Technical Report; Prepared for the NSRP Environmental Technology Panel, by Concurrent Technologies Corporation (CTC): Johnstown, PA, 2009

6. *Development of Welding Emission Factors for Cr and Cr(VI) with a Confidence Level*, Journal of the Air & Waste Management Association (AWMA), 59:5, 619-626, 2009

APPENDIX A – STAINLESS STEEL

Welding Process	Reference	Electrode	Test #	# Runs	Shielding Gas Used	TSP EF (lb/lb)	Cr EF (lb/lb)	Cr(VI) EF (lb/lb)	Mn EF (lb/lb)	Ni EF (lb/lb)	Pb EF (lb/lb)	Cd EF (lb/lb)	Notes
FCAW	NSRP 0587	316	12	1 of 3	Yes	3.34E-01	1.86E-03	7.07E-05	2.22E-02	1.60E-01	0.00E+00	0.00E+00	
FCAW	NSRP 0587	316	12	2 of 3	Yes	4.42E-01	3.04E-03	3.35E-05	2.85E-02	2.21E-01	0.00E+00	0.00E+00	
FCAW	NSRP 0587	316	12	3 of 3	Yes	3.74E-01	ND	6.34E-05	0.00E+00	ND	0.00E+00	0.00E+00	
FCAW	NSRP 0587	309	11	1 of 3	Yes	1.94E-01	2.42E-03	1.12E-04	6.35E-03	8.85E-02	6.38E-05	8.32E-06	*
FCAW	NSRP 0587	309	11	2 of 3	Yes	2.09E-01	2.82E-03	6.67E-05	6.90E-03	1.12E-01	0.00E+00	9.63E-06	
FCAW	NSRP 0587	309	11	3 of 3	Yes	1.89E-01	2.86E-03	2.65E-05	7.72E-03	1.10E-01	6.40E-05	0.00E+00	
FCAW	ESAB	309 Xtra	ESAB-3	1 of 1	Yes	--	ND	2.02E-05	7.58E-04	1.37E-04	ND	--	
FCAW	CARB	309LT-1	CARB-5	1 of 6	Yes	--	ND	1.54E-05	ND	ND	ND	--	
FCAW	CARB	309LT-1	CARB-5	2 of 6	Yes	--	ND	1.51E-05	ND	ND	ND	--	
FCAW	CARB	309LT-1	CARB-5	3 of 6	Yes	--	ND	1.39E-05	ND	ND	ND	--	
FCAW	CARB	309LT-1	CARB-5	4 of 6	Yes	--	ND	1.49E-05	ND	ND	ND	--	
FCAW	CARB	309LT-1	CARB-5	5 of 6	Yes	--	ND	1.43E-05	ND	ND	ND	--	
FCAW	CARB	309LT-1	CARB-5	6 of 6	Yes	--	ND	1.32E-05	ND	ND	ND	--	
FCAW	NSRP 0587	309	3	1 of 3	No	3.08E-01	2.07E-04	2.53E-04	4.04E-03	5.31E-03	1.06E-04	2.13E-05	
FCAW	NSRP 0587	309	3	2 of 3	No	2.71E-01	ND	8.18E-05	4.44E-03	4.72E-03	0.00E+00	0.00E+00	
FCAW	NSRP 0587	309	3	3 of 3	No	3.19E-01	2.06E-04	4.95E-05	4.16E-03	7.21E-03	8.75E-05	0.00E+00	
FCAW	NSRP 0587	316	13	1 of 3	No	3.47E-01	7.29E-03	5.16E-04	1.32E-02	3.18E-01	8.83E-05	0.00E+00	
FCAW	NSRP 0587	316	13	2 of 3	No	4.44E-01	8.52E-03	2.37E-04	1.56E-02	3.73E-01	0.00E+00	1.20E-05	
FCAW	NSRP 0587	316	13	3 of 3	No	3.26E-01	ND	2.78E-05	ND	ND	0.00E+00	ND	
FCAW	CARB	E309LT-1	CARB-5	1 of 1	No	--	ND	2.57E-04	ND	ND	ND	--	
FCAW	AP-42	E316T-3	Ref 21	Sum of 4	No	5.20E-03	2.65E-04	1.40E-04	2.50E-04	2.44E-04	--	--	
FCAW	CTC-09	E308LT-1	--	1 of 6	Yes	3.97E-03	3.17E-04	6.10E-06	3.44E-04	4.20E-05	1.30E-06	--	
FCAW	CTC-09	E308LT-1	--	2 of 6	Yes	4.36E-03	3.36E-04	7.50E-06	3.69E-04	4.40E-05	1.40E-06	--	
FCAW	CTC-09	E308LT-1	--	3 of 6	Yes	5.54E-03	3.21E-04	6.60E-06	3.49E-04	4.20E-05	1.30E-06	--	
FCAW	CTC-09	E308LT-1	--	4 of 6	Yes	5.95E-03	4.36E-04	7.50E-06	4.76E-04	5.90E-05	1.70E-06	--	
FCAW	CTC-09	E308LT-1	--	5 of 6	Yes	6.43E-03	5.05E-04	2.08E-05	5.05E-04	6.90E-05	1.70E-06	--	
FCAW	CTC-09	E308LT-1	--	6 of 6	Yes	7.35E-03	6.43E-04	2.62E-05	5.97E-04	7.80E-05	1.90E-06	--	
FCAW	CTC-09	E309LT-1	--	1 of 6	Yes	6.60E-03	5.56E-04	8.00E-06	4.24E-04	7.50E-05	8.00E-07	--	
FCAW	CTC-09	E309LT-1	--	2 of 6	Yes	5.82E-03	5.37E-04	6.00E-06	4.08E-04	6.70E-05	8.00E-07	--	
FCAW	CTC-09	E309LT-1	--	3 of 6	Yes	5.54E-03	4.69E-04	6.45E-05	3.54E-04	5.10E-05	8.00E-07	--	
FCAW	CTC-09	E309LT-1	--	4 of 6	Yes	8.43E-03	1.00E-03	6.40E-06	4.79E-04	2.16E-04	8.00E-07	--	
FCAW	CTC-09	E309LT-1	--	5 of 6	Yes	7.90E-03	8.96E-04	6.60E-05	4.32E-04	2.11E-04	9.00E-07	--	
FCAW	CTC-09	E309LT-1	--	6 of 6	Yes	7.54E-03	7.07E-04	7.25E-05	3.96E-04	1.65E-04	8.00E-07	--	

Notes

* Data point 1.12E-01 (g/kg) for Cr(VI) was determined to be an outlier (nonparametric box-plot) and was not used for EF determination

ND stands for "not determined"

APPENDIX B – MILD STEEL

Welding Process	Reference	Electrode	Test #	# Runs	Shielding Gas Used	TSP EF (lb/lb)	Cr EF (lb/lb)	Cr(VI) EF (lb/lb)	Mn EF (lb/lb)	Ni EF (lb/lb)	Pb EF (lb/lb)	Cd EF (lb/lb)	Calc Cr(VI) EF (lb/lb)	Notes
FCAW	AP-42	E70T-1	Ref 12	1 of 5	Yes	--	2.40E-06	ND	1.30E-03	3.60E-06	ND	--	2.40E-07	
FCAW	AP-42	E70T-1	Ref 12	2 of 5	Yes	--	1.46E-06	ND	6.94E-04	2.19E-06	ND	--	1.46E-07	
FCAW	AP-42	E70T-1	Ref 12	3 of 5	Yes	--	1.54E-06	ND	1.11E-03	6.16E-06	ND	--	1.54E-07	
FCAW	AP-42	E70T-1	Ref 12	4 of 5	Yes	--	3.76E-06	ND	1.27E-03	7.52E-06	ND	--	3.76E-07	
FCAW	AP-42	E70T-1	Ref 12	5 of 5	Yes	--	3.60E-06	ND	1.22E-03	7.20E-06	ND	--	3.60E-07	
FCAW	AP-42	E70T-1	Ref 46	1 of 6	Yes	--	ND	ND	8.58E-04	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 46	2 of 6	Yes	--	ND	ND	1.63E-03	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 46	3 of 6	Yes	--	ND	ND	1.17E-03	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 46	4 of 6	Yes	--	ND	ND	1.50E-03	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 46	5 of 6	Yes	--	ND	ND	7.49E-04	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 46	6 of 6	Yes	--	ND	ND	7.73E-04	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 48	1 of 4	Yes	--	ND	ND	5.50E-04	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 48	2 of 4	Yes	--	ND	ND	6.00E-04	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 48	3 of 4	Yes	--	ND	ND	5.50E-04	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 48	4 of 4	Yes	--	ND	ND	6.00E-04	ND	ND	--	--	
FCAW	AP-42	E70T-1	Ref 51	1 of 1	Yes	--	1.13E-06	ND	7.83E-04	5.05E-07	ND	--	1.13E-07	
FCAW	AP-42	E70T-2	Ref 12	1 of 2	Yes	--	1.19E-06	ND	1.25E-03	2.38E-06	ND	--	1.19E-07	
FCAW	AP-42	E70T-2	Ref 12	2 of 2	Yes	--	9.80E-07	ND	1.03E-03	1.96E-06	ND	--	9.80E-08	
FCAW	AP-42	E70T-4	Ref 12	1 of 6	No	--	1.70E-06	ND	1.19E-04	8.50E-06	ND	--	1.70E-07	
FCAW	AP-42	E70T-4	Ref 12	2 of 6	No	--	1.46E-06	ND	2.04E-04	2.92E-06	ND	--	1.46E-07	
FCAW	AP-42	E70T-4	Ref 12	3 of 6	No	--	2.18E-06	ND	2.18E-04	1.31E-05	ND	--	2.18E-07	
FCAW	AP-42	E70T-4	Ref 12	4 of 6	No	--	1.90E-06	ND	3.42E-04	5.70E-06	ND	--	1.90E-07	
FCAW	AP-42	E70T-4	Ref 12	5 of 6	No	--	2.30E-06	ND	3.68E-04	4.60E-06	ND	--	2.30E-07	
FCAW	AP-42	E70T-4	Ref 12	6 of 6	No	--	2.60E-06	ND	4.94E-04	5.20E-06	ND	--	2.60E-07	
FCAW	AP-42	E70T-4	Ref 46	1 of 3	No	--	ND	ND	4.39E-04	1.33E-06	ND	--	--	
FCAW	AP-42	E70T-4	Ref 46	2 of 3	No	--	ND	ND	6.12E-04	1.33E-06	ND	--	--	
FCAW	AP-42	E70T-4	Ref 46	3 of 3	No	--	ND	ND	1.33E-04	1.33E-06	ND	--	--	
FCAW	AP-42	E70T-4	Ref 48	1 of 4	No	--	ND	ND	3.60E-04	ND	ND	--	--	
FCAW	AP-42	E70T-4	Ref 48	2 of 4	No	--	ND	ND	4.00E-04	ND	ND	--	--	
FCAW	AP-42	E70T-4	Ref 48	3 of 4	No	--	ND	ND	4.00E-04	ND	ND	--	--	
FCAW	AP-42	E70T-4	Ref 48	4 of 4	No	--	ND	ND	4.00E-04	ND	ND	--	--	
FCAW	AP-42	E70T-5	Ref 12	1 of 8	Yes	--	8.80E-07	ND	6.78E-04	3.52E-06	ND	--	8.80E-08	
FCAW	AP-42	E70T-5	Ref 12	2 of 8	Yes	--	1.13E-06	ND	8.81E-04	3.39E-06	ND	--	1.13E-07	
FCAW	AP-42	E70T-5	Ref 12	3 of 8	Yes	--	2.94E-06	ND	1.13E-03	2.94E-06	ND	--	2.94E-07	
FCAW	AP-42	E70T-5	Ref 12	4 of 8	Yes	--	1.22E-06	ND	1.02E-03	3.66E-06	ND	--	1.22E-07	
FCAW	AP-42	E70T-5	Ref 12	5 of 8	Yes	--	3.76E-06	ND	2.26E-03	1.88E-06	ND	--	3.76E-07	
FCAW	AP-42	E70T-5	Ref 12	6 of 8	Yes	--	3.46E-06	ND	1.52E-03	3.46E-06	ND	--	3.46E-07	
FCAW	AP-42	E70T-5	Ref 12	7 of 8	Yes	--	5.52E-06	ND	1.47E-03	5.52E-06	ND	--	5.52E-07	
FCAW	AP-42	E70T-5	Ref 12	8 of 8	Yes	--	4.46E-06	ND	2.68E-03	2.23E-06	ND	--	4.46E-07	
FCAW	AP-42	E70T-5	Ref 46	1 of 1	Yes	--	ND	ND	2.26E-03	ND	ND	--	--	
FCAW	AP-42	E70T-5	Ref 48	1 of 4	Yes	--	ND	ND	7.20E-04	ND	ND	--	--	
FCAW	AP-42	E70T-5	Ref 48	2 of 4	Yes	--	ND	ND	8.00E-04	ND	ND	--	--	
FCAW	AP-42	E70T-5	Ref 48	3 of 4	Yes	--	ND	ND	8.40E-04	ND	ND	--	--	
FCAW	AP-42	E70T-5	Ref 48	4 of 4	Yes	--	ND	ND	8.80E-04	ND	ND	--	--	

FCAW	AP-42	E70T-7	Ref 12	1 of 3	No	--	3.45E-05	ND	1.70E-04	9.20E-05	ND	--	3.45E-06
FCAW	AP-42	E70T-7	Ref 12	2 of 3	No	--	2.90E-06	ND	2.15E-04	1.16E-05	ND	--	2.90E-07
FCAW	AP-42	E70T-7	Ref 12	3 of 3	No	--	4.10E-06	ND	3.12E-04	1.23E-05	ND	--	4.10E-07
FCAW	AP-42	E70T-G	Ref 12	1 of 5	Yes	--	7.50E-07	ND	1.07E-03	2.18E-05	ND	--	7.50E-08
FCAW	AP-42	E70T-G	Ref 12	2 of 5	Yes	--	2.49E-06	ND	1.16E-03	5.40E-05	ND	--	2.49E-07
FCAW	AP-42	E70T-G	Ref 12	3 of 5	Yes	--	7.05E-07	ND	9.38E-04	2.12E-06	ND	--	7.05E-08
FCAW	AP-42	E70T-G	Ref 12	4 of 5	Yes	--	2.52E-06	ND	1.18E-03	5.46E-05	ND	--	2.52E-07
FCAW	AP-42	E70T-G	Ref 12	5 of 5	Yes	--	2.94E-06	ND	1.53E-03	4.02E-05	ND	--	2.94E-07
FCAW	AP-42	E71T-1	Ref 12	1 of 7	Yes	--	2.70E-06	ND	1.22E-03	3.60E-06	ND	--	2.70E-07
FCAW	AP-42	E71T-1	Ref 12	2 of 7	Yes	--	ND	ND	ND	ND	ND	--	--
FCAW	AP-42	E71T-1	Ref 12	3 of 7	Yes	--	7.30E-07	ND	7.30E-04	2.19E-06	ND	--	7.30E-08
FCAW	AP-42	E71T-1	Ref 12	4 of 7	Yes	--	1.52E-06	ND	1.09E-03	3.80E-06	ND	--	1.52E-07
FCAW	AP-42	E71T-1	Ref 12	5 of 7	Yes	--	1.94E-06	ND	1.39E-03	4.85E-06	ND	--	1.94E-07
FCAW	AP-42	E71T-1	Ref 12	6 of 7	Yes	--	4.02E-06	ND	1.05E-03	5.36E-06	ND	--	4.02E-07
FCAW	AP-42	E71T-1	Ref 12	7 of 7	Yes	--	2.02E-06	ND	1.06E-03	6.06E-06	ND	--	2.02E-07
FCAW	AP-42	E71T-1	Ref 51	1 of 1	Yes	--	1.68E-06	ND	9.72E-04	4.80E-07	ND	--	1.68E-07
FCAW	AP-42	E71T-11	Ref 12	1 of 3	No	--	1.90E-06	ND	2.28E-04	5.70E-06	ND	--	1.90E-07
FCAW	AP-42	E71T-11	Ref 12	2 of 3	No	--	2.10E-06	ND	2.52E-04	6.30E-06	ND	--	2.10E-07
FCAW	AP-42	E71T-11	Ref 12	3 of 3	No	--	1.70E-06	ND	2.04E-04	5.10E-06	ND	--	1.70E-07
FCAW	NSRP 0587	E71-M	6	1 of 3	Yes	1.24E-01	1.96E-05	8.69E-07	1.34E-02	1.99E-03	5.21E-05	0.00E+00	1.96E-06
FCAW	NSRP 0587	E71-M	6	2 of 3	Yes	1.22E-01	5.09E-05	5.08E-05	2.18E-02	0.00E+00	4.58E-05	1.27E-05	5.09E-06
FCAW	NSRP 0587	E71-M	6	3 of 3	Yes	1.64E-01	4.10E-04	2.83E-05	ND	0.00E+00	0.00E+00	0.00E+00	4.10E-05 *
FCAW	AP-42	E110T5-K3	Ref 12	Sum of 1	Yes	--	2.08E-06	ND	2.02E-03	1.12E-04	ND	--	2.08E-07 **
FCAW	AP-42	14Mn-4Cr	Ref 11	Sum of 6	No	--	1.05E-03	ND	1.38E-02	1.24E-03	ND	--	1.05E-04 **
FCAW	AP-42	14Mn-4Cr	Ref 11	Sum of 5	No	--	8.84E-04	ND	1.38E-02	2.08E-04	ND	--	8.84E-05 **
FCAW	NSRP 0587	E770	7	1 of 3	Yes	1.72E-01	2.42E-05	2.65E-06	2.07E-02	8.62E-03	6.73E-05	0.00E+00	2.42E-06 ***
FCAW	NSRP 0587	E770	7	2 of 3	Yes	1.71E-01	5.09E-05	0.00E+00	3.26E-02	1.20E-02	9.88E-05	2.39E-05	5.09E-06 ***
FCAW	NSRP 0587	E770	7	3 of 3	Yes	1.36E-01	6.24E-05	2.46E-06	2.36E-02	1.11E-02	9.36E-05	1.42E-05	6.24E-06 ***
FCAW	NSRP 0587	71-T GS	4	1 of 3	No	5.28E-01	9.31E-05	3.85E-05	2.93E-02	0.00E+00	2.64E-04	0.00E+00	9.31E-06
FCAW	NSRP 0587	71-T GS	4	2 of 3	No	5.01E-01	1.58E-04	5.56E-05	4.55E-02	0.00E+00	3.71E-04	0.00E+00	1.58E-05
FCAW	NSRP 0587	71-T GS	4	3 of 3	No	6.24E-01	ND	2.21E-05	9.54E-03	1.89E-01	2.30E-04	0.00E+00	--
FCAW	NSRP 0587	70T	9	1 of 3	No	1.88E-01	6.72E-05	1.00E-05	1.00E-02	1.04E-02	0.00E+00	0.00E+00	6.72E-06
FCAW	NSRP 0587	70T	9	2 of 3	No	1.92E-01	8.46E-05	7.69E-06	1.46E-02	9.23E-03	8.85E-05	1.92E-05	8.46E-06
FCAW	NSRP 0587	70T	9	3 of 3	No	1.62E-01	1.14E-04	9.31E-06	1.09E-02	6.19E-03	6.19E-05	0.00E+00	1.14E-05

Notes
* 4.10E-01 (g/kg) exluded per historical industry comments
** Rods E110T5-K3 and 14Mn-4Cr did not fit the parameters of the study and were excluded from test data comparison
*** Assumed E770 to be TRI-MARK TM770 (AWS classification E71T-1M)

ND stands for "not determined"