Shipyard Welding Emission Factor Development

William C. Mener
LFR Levine-Fricke, 5 Johnson Drive, P.O. Box 130, Raritan, NJ 08869
william.mener@lfr.com

Peter L. Rosen
LFR Levine-Fricke, 3150 Bristol Street, Suite 250, Costa Mesa, CA 92626
peter.rosen@lfr.com

Dana M. Austin
Dana M. Austin Environmental Consulting, Inc., 11111-2A San Jose Blvd., Suite 312,
Jacksonville, FL 32223
dmaustin@mediaone.net

Wayne S. Holt
Atlantic Marine Inc., 8500 Heckscher Drive, Jacksonville, FL 32226
wholt@atlanticmarine.com

ABSTRACT

LFR Levine·Fricke (LFR) teamed with Dana M. Austin Environmental (DMAE) and Atlantic Marine Inc. (AMI) to develop emission factors for shipyard welding operations. The National Shipbuilding Research Program (NSRP) funded the project.

Prior to the study, there were little published data on shipyard-specific welding emissions. The goal of the project was to develop emission factors for common welding processes at shipyards. The emission factors developed will be used in a guidance document to help shipyards estimate welding emissions for use in Toxic Release Inventory (TRI) reports, air quality planning, and employee exposure compliance. The contaminants of concern included metals, total particulate, PM_{10} and $PM_{2.5}$.

An extensive survey of over 200 shipyards was conducted to identify the most common types of welding rod and welding processes utilized. The survey also identified typical Hazardous Air Pollutant (HAP) components contained in common shipyard welding rods as well as overall composition.

LFR developed a test protocol that identified the welding methods and types of rods to be used in the program. The protocol also included details on fume capture and sampling methods. LFR designed a test enclosure to capture and sample fumes from welding operations within the enclosure. The test enclosure met capture specifications of USEPA Method 204 and USEPA reference methods were utilized for sample collection and analysis. Total mass of welding rod burned was tracked to correlate consumption rates with measured emission rates of the contaminants of concern. Emission factors were developed for each combination of welding methods and rods.

INTRODUCTION

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Prior to the study, there were little published data on shipyard-specific welding emissions. While the United States Environmental Protection Agency (U.S. EPA*) Compilation of Air Pollutant Emission*

Factors (AP-42) provides some data on welding emission factors, these are generally not consistent with the processes and types of welding rods currently used at United States shipyards. The goal of the project was to develop emission factors for common welding processes at shipyards. The emission factors developed will be used in a guidance document to help shipyards estimate welding emissions for use in Toxic Release Inventory (TRI) reports, air quality planning, and employee exposure compliance. The contaminants of concern included metals, total particulate, PM_{10} and $PM_{2.5}$.

The scope of the project included a survey to identify typical welding procedures conducted at shipyards, development of an emission factor test plan, implementation of the test plan, and development of emission factors. The amount of available funding from the NSRP limited the testing program to two welding methods. However, detailed testing was conducted for these two methods using various types of welding rods. The tests were conducted from October 4 through 13, 1999 at the AMI Mayport Shipyard in Jacksonville, FL. The results of the study showed emission factors for particulates to be similar to those in AP-42. However, the results for metals were generally lower than those presented in previous studies.

WELDING PROCESSES BACKGROUND

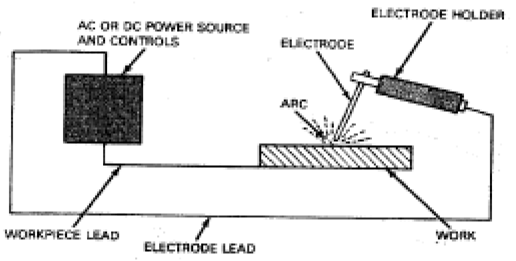
There are more than 80 different types of welding operations, including brazing, thermal cutting, and gauging, in commercial use. By definition, welding is the process of joining two metal parts by melting the parts at the joint and filling the space with molten metal. In welding and similar operations, such as brazing, thermal cutting, and gauging, the most frequently used method for generating heat is obtained either from an electric arc or a gas-oxygen flame. The shipyard survey portion of the project showed that arc welding is the most common welding process conducted at United States shipyards. Project funding limited the work scope to shielded metal arc welding (SMAW) and submerged arc welding (SAW), which were identified in the survey as the two most common processes with high emissions potential. Arc welding in general and SMAW and SAW processes are described below.

Arc Welding

Electric arc welding, the most frequently used process, includes many different variations that involve various types of electrodes, fluxes, shielding gases, and types of equipment. Electric arc welding can be divided into processes using non-consumable electrodes and consumable electrodes. In electric arc welding, a flow of electricity across the gap from the tip of the welding electrode to the base metal creates the heat needed for melting and joining the metal parts. The electric current melts both the electrode and the base metal at the joint to form a molten pool, which solidifies upon cooling. A description of each of the types of electric arc welding process included in the study is provided below.

Shielded Metal Arc Welding

SMAW is the most widely used electric arc welding process and the first type to use consumable electrodes. The process also is referred to as manual metal arc welding (MMAW). Shielded metal arc welding uses heat that is produced by an electric arc to melt the metals. The electric arc is maintained between the welding joint at the surface of the base metal and the tip of the covered welding electrode (Figure 1). During operation, the core rod conducts electric current to produce the arc and provides filler metal for the joint. The core of the covered electrode consists of either a solid metal rod of drawn or cast material, or a solid metal rod fabricated by encasing metal powders in a metallic sheath. The electrode covering provides stability to the arc and protects the molten metal by the creation of shielding gases from the vaporization of the electrode cover.



Basic SMAW apparatus.

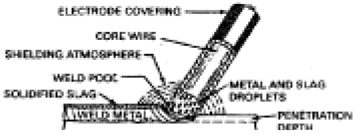


Figure 1. Shielded Metal Arc Welding
Source: Background Document for AP-42 Section 12.19

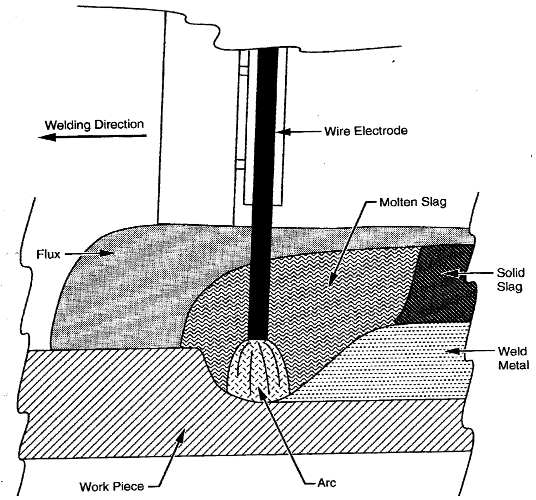


Figure 2. Submerged Arc Welding
Source: Background Document for AP-42 Section 12.19

The arc characteristics of the electrode and the mechanical properties, chemical composition, and metallurgical structure of the weld are influenced by the type of shielding used, along with other ingredients within the covering and core wire. Each type of electrode used in SMAW has a different type of electrode covering, depending on the application.

The advantages of the SMAW process include its simplicity, low cost, portability, and the fact that a shielding gas is not needed. One restriction of SMAW is that the deposition cycle is normally less than for processes using continuous electrodes.

Submerged Arc Welding

SAW produces an arc between a bare metal electrode and the work contained in a blanket of granular fusible flux (Figure 2). The flux submerges the arc and welding pool. Generally, the electrode serves as the filler material, although a welding rod or metal granules may be added. The flux covering the arc in submerged arc welding is an important factor in the process. The flux's role influences the stability of the arc and the mechanical and chemical properties of the final weld deposit. The quality of the weld is dependent on the handling and care of the flux.

Medium and heavy fabrication industries use the SAW process for fillet and main butt joints in pipe, cylinders, pressure vessels, columns, and beams. Generally, the welding head is fully automatic and mounted on a manipulator or carriage; however, for fillet welding, hand held torches are available. Although SAW is limited to the down hand and horizontal positions, these positions can be utilized by informed design and job positioning. The process is also restricted by the high proportion of time needed to align the torch with the joint.

WELDING EMISSIONS BACKGROUND

The main pollutants of concern generated during electric arc welding operations are particulate matter and particulate phase hazardous air pollutants. The quantity of emissions released depends largely on the type of welding process used and its operating conditions. Depending on the choice of electrode and its diameter and composition, emissions are reduced or increased. The work piece composition also affects the quantity of fume released. Coatings on the work piece generate organic and metallic fumes (e.g., galvanized coatings, cleaners, oils, paints, etc.), depending on the particular application. Operating conditions that influence fume emissions include travel speed, voltage, current, arc length, polarity, welding position, electrode angle, and deposition rate.

The welding fume is formed by the vaporization and recondensation of metallic elements upon cooling in ambient air. The amount of the emissions generated can vary substantially from process to process. The elemental composition of the fume varies with the electrode and work piece composition. Hazardous metals listed in the 1990 Clean Air Act Amendments that have been detected in welding fume include manganese, nickel, chromium, cobalt and lead. Additionally, the hexavalent form of chrome (Chrome $^{+}$6) is also found in some welding fume emissions. The emissions of toxic air contaminants during welding have potential adverse human health impacts. Occupational exposures to welding fumes are typically controlled with ventilation and personal protective equipment. Environmental exposures are more difficult to define and potential health impacts are usually predicated using computer dispersion models and health risk assessments. As the results of the dispersion models (and therefore the health risk assessment) are directly dependent upon the emission rate of a contaminant, it is important to quantify the emissions factors of the various toxic air contaminants as accurately as possible.

STUDY PARAMETERS

The study conducted for this project consisted of several distinct tasks in accordance with the NSRP workscope, with each task predicated on the prior completed task(s). The complete results of each task were the subject of individual Task Reports. These tasks are summarized below. The final report summarized the overall results of the project.

Task One – Shipyard Survey

Task One consisted of the development of a survey to ascertain which welding processes and types of welding/rod were in most common usage in the US Shipbuilding and Repair Industry. Additionally, based upon the result of the survey, the types of welding rod/wire were evaluated to determine which ones would have emissions with the greatest potential health impact. Based upon the survey and the evaluation, two welding processes (SMAW and SAW), eight types of rod/wire, and nine variables (three particulate size fractions and six metals) were selected for testing. Table 1 summarizes the combinations of welding methods and rods selected for the program.

Table 1. Rods/wires and welding processes selected for emission factor testing

Rod/Wire American Welding Society Classification Number	Welding Process
E308-16, E308L-16	Shielded Metal Arc Welding
E309-16	Shielded Metal Arc Welding
E308-17, E308l-17	Shielded Metal Arc Welding
E309-17, E309L-17	Shielded Metal Arc Welding
E316-16, E316L-16	Shielded Metal Arc Welding
E308-16, E308H-16	Shielded Metal Arc Welding
ER309, ER309L	Submerged Arc Welding
ER316, ER316L	Submerged Arc Welding

Task Two – Development of Test Plan

Task Two consisted of the development of a sampling and testing protocol. The plan included details on how welding was to be conducted under controlled test conditions within the test enclosure (see Task 3). Metal parts were welded utilizing the combination of methods and rods/wires described in Table 1. Test durations ranged from approximately one to two hours. It was anticipated that three test runs would be completed for each condition. However, equipment difficulties resulted in completion of only two runs for each of the SAW tests.

U.S. EPA Reference Methods were utilized for sampling the welding fumes within the enclosure exhaust duct. The test methods and contaminants that were analyzed for are summarized in Table 2.

Table 2. Parameters and test methods utilized for emission factor development

Parameter	Test Method
Flow Rate	U.S. EPA Reference Method 1, *Sample and Velocity Traverses for Stationary Sources*
	U.S. EPA Reference Method 2, *Determination of Stack Gas Velocity and Volumetric Flow Rate (Type-S Pitot Tube)*
Moisture	U.S. EPA Reference Method 4, *Determination of Moisture Content in Stack Gas*
Total Suspended Particulate	U.S. EPA Reference Method 5, *Determination of Particulate Emissions from Stationary Sources*
Particulate Matter less than 10 microns and less than 2.5 microns	Modified version of U.S. EPA Reference Method 201A, *Determination of PM10 Emissions (Constant Sampling Rate Procedure)*
	U.S. EPA Reference Method 202, *Determination of Condensible Particulate Emissions from Stationary Sources*
	U.S. EPA Draft Method for Determination of PM10 and PM2.5 Emissions(Constant Sampling Rate Procedure; June 8, 1999)
Metals – Nickel, Manganese, Lead, Cadmium, and Total Chromium	U.S. EPA Reference Method 29, *Determination of Metals Emissions from Stationary Sources*
Metals – Hexavalent Chromium	U.S. EPA Reference Method 306, *Determination of Chromium Emissions from Decorative and Hard Chromium Electroplating and Anodizing Operations*

The total mass of rod/wire utilized during each test was recorded. An average weight of each type of rod was determined using an analytical balance. The total number of rods consumed for each test was noted, and unconsumed portions of rods were weighed and subtracted from the total used for each test. This information, along with the emission rate data, was used to calculate emission factors. Details on specific test methods were included in the test plan.

Task Three – Design and Construction of Test Facility

In order to develop emission factors for shipyard welding operations, it was necessary to design and construct a facility to collect and exhaust welding fumes and allow collection of exhaust samples. Welding was conducted within the test facility and fumes were vented through the system exhaust. An existing paint spray booth was utilized as the test facility. This spray booth was modified to facilitate complete fume collection. The spray booth prior to modification is shown in Figure 3.

Figure 3. Test Enclosure Prior to Modification

The spray booth measured approximately 14 feet wide by 22 feet long by 10 feet high. To configure the spray booth as the sample collection chamber some modifications were made to meet USEPA's requirements for a temporary total enclosure while still allowing safe access for the source sampling team. The spray booth was operated in reverse of its normal configuration, with makeup air being supplied through the exhaust stack. An exhaust fan and horizontal duct were attached to the front of the booth at one of the normal makeup air inlet points. All other inlets were blocked off. Approximately 4000 scfm of air was exhausted from the test facility resulting in over 75 air changes per hour. In this configuration, the test facility met the specifications of USEPA Method 204, *Criteria for and Verification of a Permanent or Temporary Total Enclosure* and 100% fume capture was assumed.

The inlet air to the test facility was filtered with standard HVAC filters. The exhaust duct was of horizontal configuration and measured 22 inches square by approximately 32 feet long. Three 5-inch diameter sample ports were installed in the vertical portion of the exhaust duct approximately 17 feet downstream of the exhaust blower transition. These ports were used for PM_{10} and $PM_{2.5}$ sampling. Three sets of 3-inch ports (5 ports each in the vertical portion of the duct) were also installed in the duct and utilized for total particulate and metals sampling. All sample ports met the criteria of USEPA Method 1, *Sample and Velocity Traverses for Stationary Sources.*

Welding was completed within the test facility by experienced welders and all fumes were vented through the exhaust duct. Sampling equipment was set up along the exhaust duct, and samples were collected and analyzed for various components as summarized in Table 2. Figures 4 and 5 show an overview of the completed test facility and the test facility interior, respectively.

Figure 4. Overview of Test Enclosure

Figure 5. Test Enclosure Interior

Task Four – Implementation of Testing Program

Task Four consisted of the performance of the tests and the collection of the test samples, in accordance with the protocol established in Task Two and the test facility design described in Task Three. Some field adjustments were made to the test plan based on unforeseen conditions, but for the most part, the proposed procedures were followed.

Task Five – Chemical Analysis of Fume Samples

Task Five consisted of the chemical analysis of the samples, and the reduction of the data to allow the development of emission factors for the selected variables. Fume samples were analyzed in accordance with the USEPA Reference Methods specified in the Test Plan. Using the analytical data, source sampling data, and measured exhaust duct flow rate, mass emission rates were calculated for each test. These data, along with the rod/wire use amounts, were used to calculate emission factors for each test. The emission factors are presented on a mass emission rate per mass of rod consumed basis.

The analytical results were summarized in Excel spreadsheets. Length limitations for this paper prevent inclusion of the analytical data. However, a description of the data analyses follow.

Particulate emissions typically consist of a filterable fraction (front-half) and condensible fraction (back-half). Therefore, the data utilized for emission factor development include the total of the condensible and filterable fractions for total suspended particulate (TSP), particulate matter less than 10 microns (PM_{10}), and particulate matter less than 2.5 microns ($PM_{2.5}$).

The analytical results for metals (other than hexavalent chromium) include both the filterable and condensible fractions. Both fractions were digested in the laboratory, combined and analyzed as a single sample. Since the hexavalent chromium sampling method does not require the use of a filter, only the back-half samples were analyzed.

Some anomalies in the data were noted for two test runs (submerged arc welding, E308-17, E308L-17 – Test No. 6, Runs 2 and 3) where the TSP emission factors are less than those for PM_{10} and $PM_{2.5}$. This is not possible since TSP represents total particulates and PM_{10} and $PM_{2.5}$ represent a certain fraction of TSP. These anomalies are likely due to sampling and analytical limitations that are sometimes experienced with low emission rates such as those demonstrated during this sampling program. In addition, it is commonly accepted that welding fume consists of a high percentage of small diameter particulate matter. Most of the data for the other tests conducted during this program support that belief, with very small differences between TSP and PM_{10} emission factors. A similar disparity exists for one other test run (submerged arc welding, E308-17, E308H-17- Test 8, Run 1) where TSP numbers are slightly higher than PM_{10}. It is not believed that these anomalies affect the overall validity of the test data. It should also be noted that the analytical results for cadmium emissions were below method detection limits for several runs. In these cases, the detection limits were used to calculate emission factors.

DEVELOPMENT OF EMISSION FACTORS

Emission factors were developed for the particulate size fractions and metals as sampled and analyzed in Tasks Four and Five. The emission factors were derived using the following equation.

Equation (1): Emission Factor Development

$$\frac{\text{Analytical Results (lbs)}}{\text{Meter Box Reading (dscf)}} \times \text{Air Volume (cuft/min)} \times \frac{\text{Lenght of Test (min)}}{\text{Mass of Rod (lbs)}} = \text{Emission Factor}$$

where:

Analytical Results = the mass in pounds of variable measured.
Meter Box Reading = the amount of air volume in cubic feet drawn through the sample collection equipment.

Air Volume = the airflow in cubic feet per minute through the sampling duct.
Length of Test = the amount of time in minutes the testing was conducted.
Mass of Rod = the mass of welding rod or wire consumed during the test period.

This equation results in an emission factor (EF) for each variable, expressed in units of pounds emitted/pound welding rod consumed.

An EF was calculated based upon the result of each run of each test (three runs per test, except for SAW tests, where two runs were completed, respectively). For the purposes of developing an EF for each specific type of welding rod/wire and its associated welding process, the calculated emission factors for all the runs in each test were averaged. The resultant emission factors are presented in the following section.

WELDING ROD/PROCESS EMISSION FACTORS

Particulate Emission Factors

Particulate emission factors were calculated for three size fractions of particulates: TSP, PM_{10} and $PM_{2.5}$. The emission factors presented in the following Tables are given in units of pounds of particulates per 1,000 pounds of rod consumed.

Table 3. Particulate emission factors

Process/Materials		Emission Factors – lbs/1000lbs		
Welding Process	**Rod/Wire Type**	**TSP**	**PM10**	**PM2.5**
SMAW	E308-16, E308L-16	45.16	27.52	23.92
SMAW	E309-16	37.23	33.47	32.88
SMAW	E309-17, E309L-17	25.14	19.85	19.02
SMAW	E316-16, E316L-16	101.8	30.03	29.11
SAW	ER316, ER316L	7.95	7.76	7.53
SMAW	E308-17, E308L-17	26.73	27.09	26.14
SAW	ER309, ER309L	17.62	16.65	15.43
SMAW	E308-17, E308H-17	31.09	27.72	27.09

The emission factors calculated for particulate matter in this study are in general agreement with the results of other studies performed previously. These include the following observations:

1) The SAW welding process has a significantly lower fume generation rate than does SMAW.
2) The amount of rod that is converted to fume varies within a range of 1 to 10 percent.
3) In most instances, the great majority of particulates generated from the SMAW and SAW welding processes is 2.5 microns and less in size.

Table 4. Metals emission factors

Process/Materials		Emission Factors – lbs/1000lbs					
Welding Process	**Rod/Wire Type**	**Cd**	**Cr**	**Pb**	**Mn**	**Ni**	**Cr^{+6}**
SMAW	E308-16, E308L-16	0.00	0.60	0.02	0.34	0.05	0.15
SMAW	E309-16	0.00	0.74	0.01	0.36	0.06	0.09
SMAW	E309-17, E309L-17	0.00	0.68	0.01	0.44	0.05	0.08
SMAW	E316-16, E316L-16	0.00	0.83	0.01	0.42	0.08	0.19
SAW	ER316, ER316L	0.00	0.01	0.00	0.07	0.00	0.00
SMAW	E308-17, E308L-17	0.00	0.56	0.01	0.50	0.05	0.11
SAW	ER309, ER309L	0.00	0.01	0.01	0.09	0.01	0.00
SMAW	E308-17, E308H-17	0.00	1.18	0.00	0.85	0.22	0.18

With regard to metals emissions from welding, the following general observations can be made:

1) Metal emissions derived from the SAW process are significantly less than from the SMAW process. This is likely a result of the much lower fume generation rate observed with SAW as compared to SMAW.

2) Cadmium and lead emissions are not a significant factor using these types of welding rods and their associated welding process.
3) The emission factors for manganese, total chrome and nickel had a general positive correlation with the percentage of these metals (and metal compounds) contained in the welding rod. In other words, when the concentration of the metal increased in the rod, the amount of metal emissions also increased.
4) Manganese had the highest emission factors to rod concentration ratio in comparison to the other metal tested. In other words, a greater percentage of manganese in the rod is emitted in the fume during the rod consumption than the other metals tested.

CONCLUSIONS

The development of emission factors for welding processes and the associated types of rod and wire that can be used in those processes is difficult for several reasons. Perhaps the most important is that arc welding is a multivariate process that is difficult to subject to precisely controlled testing. Uncontrolled variables in the testing procedure can result in significant variations in the measured test parameters necessary to calculate an emission factor.

The emission factors derived from this study are believed to be accurate within the established test parameters. A review of the available literature concerning emission factors for particulates and metals, including United States Environmental Protection Agency AP-42, indicate that while the emission factors for particulates are generally similar to other studies, the emission factors for metals are generally lower than those presented in other published reports. As the testing, sampling and analytical protocols are not consistent between the various published studies and our study, we cannot identify any specific set of reasons why the emission factors derived from this study would be inconsistent with other research results.

The testing procedure designed for this study is believed to be representative of actual shipyard welding conditions, for these processes and materials. For this reason, the emission factors derived are believed to be an accurate representation of welding emission from SMAW and SAW operations at shipyards.

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KEY WORDS

Emission Factors
Submerged Arc Welding
SAW
Shielded Metal Arc Welding
SMAW
Metals
PM
PM_{10}
$PM_{2.5}$
Shipyard
Ship
Ship building
Welding
TSP
NSRP